DISSERTATION

THE USE OF THE WISDEM MODEL IN THE SIMULATION OF WEED SHIFTS IN GLYPHOSATE-TOLERANT CROPPING SYSTEMS

Volume I
Chapters 1 - 4

Submitted by

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Colorado State University
Fort Collins, Colorado
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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY JOHN R. WITHROW, JR. ENTITIED *THE USE OF THE WISDEM MODEL IN THE SIMULATION OF WEED SHIFTS IN GLYPHOSATE-TOLERANT CROPPING SYSTEMS* BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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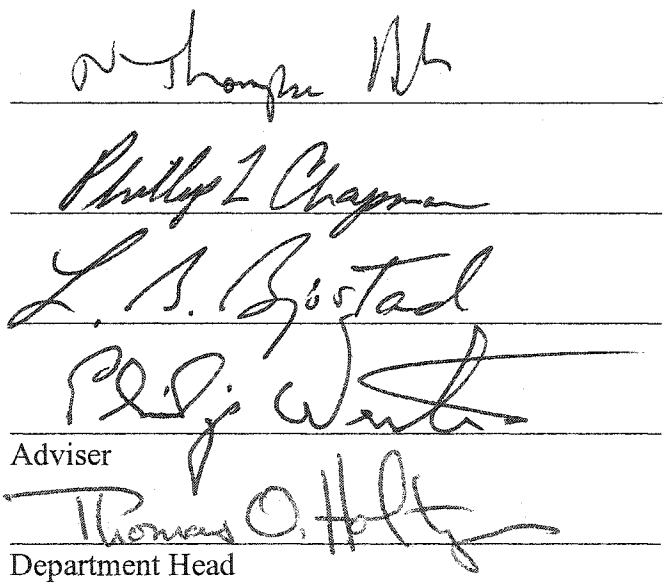

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ABSTRACT OF DISSERTATION

THE USE OF THE WISDEM MODEL IN THE SIMULATION OF WEED SHIFTS IN GLYPHOSATE-TOLERANT CROPPING SYSTEMS

WISDEM (Weed Interference and Simple Demographic Model) is a decision-aid model developed initially by Wiles et al. (1996) and recently augmented in response to some major theoretical work by Canner, Wiles, and McMaster (2002). This model has been significantly upgraded by the present author and is presented as an ecologically-based approach to the simulation of weed shifts as well as a realistic decision-aid management tool for glyphosate-tolerant cropping systems, specifically for selecting optimal weed management products and optimal application timings.

This work begins with a discussion of previous modeling efforts, competition studies, and the inherent weed science concepts that provide the foundation for such models. Such a discussion provides insight into the theoretical and historical development of WISDEM.

On this theoretical level and from this historical legacy the model represents each crop rotation as a controlled sequence of scheduled plant disturbance events whose timing and intensity can be varied. Crop emergence is represented as a singular pulse event, while emergence for each weed species is depicted via an empirically derived Weibull curve. Population dynamics for each plant species are calculated via a set of proportional yield equations that estimate seed production per

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unit area for each plant species. These equations assess the competitive influence of each cohort of each plant species according to the species' relative competitive index, degree of competitive asymmetry, and emergence timing. In this way it has been postulated that much in the way of explicit multi-species plant competition can be represented through the use of empirical biological parameters that are relatively easy to obtain. It has also been postulated that additional simplification may be possible by integrating parameters associated with yield loss with parameters associated with weed seed production.

In addition, in the context of the present work two algorithmic upgrades have been implemented, one which imposes a reduction in per-plant fecundity for late-emerging weed species and the other defining an effective weed density for crop yield reduction by averaging the weed densities for each species over the crop's competitive period. These two advancements, respectively referred to as the advent of "reproductive density" and "crop competitive density" are presented along with a re-parameterization of the curves that define the emergence timings of each weed species. Sensitivity analyses are performed along with validation studies that suggest a significant improvement in WISDEM's ability to represent realistic dynamics, and to, thus, serve as an effective ecological model and decision-aid tool.

Lastly, two modeling experiments are performed on the field study from which validation comparisons have taken place. In each case various model runs are performed in an effort to find an option that is economically optimal from a long-term planning perspective. One experiment seeks to find a suitable burn-down herbicide replacement for a pre-plant tillage event, one which would effectively render the crop

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production scenario now as a "no-till" practice. The other experiment seeks to find optimal timings for the applications of Roundup Ultra™. In both instances the WISDEM model provides realistic recommendations that confirm its usability as a decision-aid tool.

This work concludes with a description of the status of the ongoing project and suggestions for further efforts.

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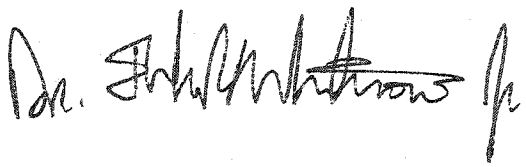
Lastly, I would like to thank the members of Immanuel Christian Reformed Church in Fort Collins, Colorado, especially John Terpstra, Dr. Larry Kieft, Dr. Christian and Laurel Hageseth, Dr. Terry and Sheri Gray, and all the members of the Immanuel youth group and Saturday men's group, all of whom participate and cultivate an atmosphere of faith that instills in each believer a heart of worship, a passion for service, and a feeling of family.

It is because of people like all those mentioned above that this project has come to a successful conclusion, thus enabling me for the first time in my life to sign my name,



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AUTOBIOGRAPHY

John R. Withrow, Jr. grew up in Waukesha, Wisconsin where he received his B. A. degree from Carroll College in 1990 with a double-major in physics and geography and a minor in mathematics. John received his master's degree in atmospheric science from Colorado State University in Fort Collins, Colorado in 1994 and his certification to teach secondary mathematics from the same institution in 1997. Since then John has taught high-school mathematics in Greeley, Colorado and has trained primary and secondary teachers and administrators in computer software in a whole host of school districts in Colorado, Wyoming, Nebraska, and Kansas.

In the spring of 2001 John began his work in the Department of Bioagricultural Sciences and Pest Management at Colorado State University, work which is documented in this Ph.D. dissertation.

In his spare time John enjoys spending time with his wife, three stepsons Chip, Bradley, and Michael, and his step-granddaughter, Sierra. His latest hobby is amateur filmmaking, where his latest works include an educational film on Clearfield technology and a dramatic film entitled "The Case of the Frozen Saints."

John also works in his church youth group, sings, plays saxophone, and finds that he has considerable difficulty keeping a straight face while writing about himself in the third person.

John is due to start a postdoctoral position as a statistician for the USDA Forest Service in the fall of 2004.

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DEDICATION

FOR WAYNE

THE BEST MENTOR AND FRIEND ONE COULD EVER HOPE TO HAVE

FOR A BOY OR A MAN

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Chapter 1.0
Introduction

"If you would converse with me, first define your terms."
Voltaire

1.1 Glyphosate and Roundup Ready™ Crops

The glyphosate herbicide, or N-(phosphonomethyl)glycine, was first discovered by Stauffer Chemical company in the 1960's as an effective plant growth regulator. Its use at higher concentrations as an herbicide was then later patented by Monsanto (Beck et al., 2001). It achieves its desired nonselective herbicidal effect via an interruption of the shikimic acid pathway which covers all aromatic amino acid biosynthesis. The compound acts as an inhibitor of the 5-enolpyruvylshikimate-3-phosphate synthase enzyme (Devine et al, 1993; Buchanan et al., 2000; Nissen, 2002), the results of which can be biochemically detected in the form of elevated levels of shikimate within the plant (Pline et al., 2002). The immediate response of the plant is an arrest of all plant growth. Plant necrosis results within a few days.

The glyphosate molecule is cationic, and, thus, binds quickly to soil particles, thus rendering it useless in terms of residual soil activity. Its usage is restricted to post-emergence foliar applications as a nonselective "burndown" herbicide (Crop Protection Reference, 2000).

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Roundup Ready™ crops were first introduced by Monsanto in 1990's as a genetically modified crop where the EPSP synthase enzyme possesses a slightly modified tertiary structure that is not inhibited by the glyphosate molecule. Thus, the standard Roundup Ready™ cropping system involves the use of such a crop (or multiple crops in rotation) with one or more of the many different formulations of glyphosate to control all weed species. An additional herbicide from a different mode of action may also be utilized to abate the establishment of glyphosate-tolerant weed populations.

The present list of crops where a Roundup Ready cultivar is available includes corn (*Zea mays*), soybeans (*Glycine max*), cotton (*Gossypium hirsutum* L.), and canola (*Brassica napus* L.). There are also indications that Roundup Ready™ sugarbeets (*Beta vulgaris* L.) and alfalfa (*Medicago sativa*) may be coming soon (Monsanto, 2003; North Dakota State University and Montana State University, 1997, respectively).

Among agronomic practices, the use of Roundup Ready™ cropping systems is presently on a very significant increase, due in no small part to its simplicity with respect to matters of weed control combined with the fact that the high nonspecific herbicidal efficacy of its associated herbicide glyphosate (also known as Roundup™) relieves the grower from a reliance on tillage for effective weed control. This tillage-free (known popularly as "no-till") system has advantages in terms of moisture loss, topsoil erosion, and maintenance of soil organic matter.

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1.2 Statement of the Problem

As a result of its prolific availability, its simplicity, and its advantages as a "no-till" system FIGURE 1.1, from Battaglin et al. (2003), displays the extent to which such cropping systems are nationally on the rise. With American agriculture taking the form of larger-scale operations, decision-making processes have needed to become less artfully qualitative and more scientifically quantitative. This combined with an ever-increasing list of weed management tools and options has spawned the advent of numerous quantitative analyses of the dynamics of weed populations and their effects on crop yield. Such studies have manifested themselves in the form of decision-aid models that have direct implications with regards to weed management and have also assisted in the scientific understanding of crop-weed interactions (e.g., Wiles et al., 1996).

General weed shift studies have been done on corn, soybeans, and cotton (Webster and Coble, 1997), but have focused on cultivars other than those tolerant to glyphosate. Reports of tolerance to glyphosate have also been reported in horseweed (*Conyza canadensis* L. Cronq.) in the United States , rigid ryegrass (*Lolium rigidum*) in Australia, and goosegrass (*Eleusine indica* L. Gaertn.) in Malaysia (van Gessel, 2001; Lorraine-Colwill et al., 2001; and Baerson et al., 2002, respectively). In addition, eventual tolerance to glyphosate has also been implicated in quackgrass (*Elytrigia repens*), black nightshade (*Solanum nigrum*), waterhemp (*Amaranthus rudis* Sauer), yellow nutsedge (*Cyperus esculentus* L.), velvetleaf (*Abutilon theophrasti* Medicus), and

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common ragweed (*Ambrosia artemisiifolia* L.) (Ziska and Teasdale, 2000; Hartzler, 1998).

In this study the implementation of a new long-term weed shift model originally created by Canner et al. (2003) is presented and discussed along with numerous validation studies to determine its effectiveness at representing the weed population dynamics resulting from multi-year representations of multi-species competition. As a result of its satisfactory representation of population dynamics, the model is presented as an effective weed management decision-making tool for the determination of optimal weed management products as well as optimal application timings in Roundup Ready™ crops.

1.3 Introduction to the Larger Work

This work begins with a three-part literature review covered in chapters 2, 3, and 4. Chapter 2 focuses on the fundamental aspects that are fairly prolific among weed population modeling studies. Chapter 3 builds on the previous chapter to focus more on special topics that are found less frequently but are still on the rise and are of significant importance. Chapter 4 focuses on the future challenges that are specific to the simulation of plant population dynamics in agronomic systems.

This study began to a large extent with a grand-scale survey that was performed to solicit expert opinion concerning weed shifts within Roundup Ready™ cropping systems.

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Chapter 5 describes the methodology and results of that survey and will be presented in publication format.

In addition to sequestering expert opinion, a large-scale field study regarding weed shifts in Roundup Ready™ cropping systems was initiated in 1998 (Westra et al., 2004). Though not a principal investigator of this study, the present author was involved in the analysis of the data. Since it pertains to the topic of this dissertation, its results are described in chapter 6, though in a publication format.

Chapters 7 and 8 then focus on the WISDEM model. Chapter 7 will describe the initial WISDEM model as it was previously developed by Canner et al. (2003) along with a thorough description of its algorithmic enhancements. Chapter 8 then shows validation results involving the WISDEM model with the dataset described in chapter 6, along with some experiments that were made possible from the success of the validations. The chapter ends with some suggestions for further research, and will also be presented in publication format.

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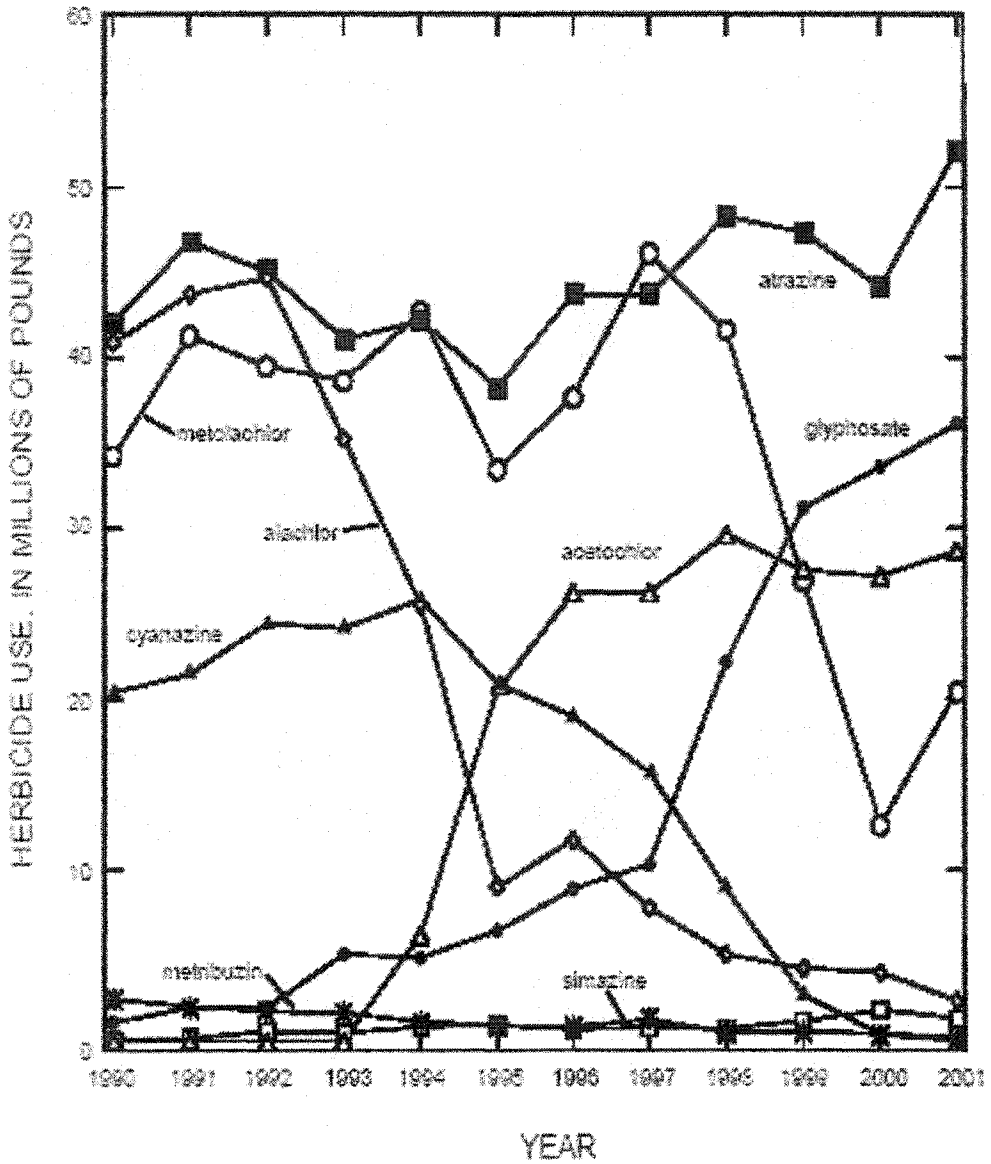

FIGURE 1.1, from Battaglin et al. (2003), showing annual changes in total usage of various herbicides in the United States.

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Chapter 2.0
Literature Review I: Basic Essentials

"If I have seen further, it is by standing on the shoulders of giants."
Isaac Newton

The pursuit of insight into the processes involved in weed population dynamics through the techniques of mathematical modeling has a long and well-documented history in weed science (Cousens and Mortimer, 1995; Kropff and van Laar, 1993). In addition, the involvement of modeling and simulation in the field of weed science appears to be on the rise, due in no small part to some significant recent paradigm shifts. Cousens et al. (1987b) described an impression that the degree of modeling efforts in weed science at that time were less than what might be expected when comparing with other disciplines, presumably due to a relatively small number of researchers trained in such methods as well as a high demand for straightforward herbicide performance testing at the expense of the more investigative studies involved in modeling. Today, in particular with the advent of herbicide tolerance in weeds, a shift towards a more long-term ecological approach to weed management has been evident, and concurrently with this new approach has come two benefits of this academic outcrossing:

1. The inclusion of a more systems-based approach to an understanding of weed management, and

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2. The advent of a wider range of mathematical techniques and computational technology towards a quantitative understanding of processes involved in such systems.

In this chapter the essential fundamentals of this history are addressed. It begins with an overall discussion of philosophy and techniques and proceeds with a history of the weed simulation efforts that focuses first on the more general modeling efforts and ends with simulations that involve more specific aspects of plant processes.

2.1 Philosophy

The reasoning behind the use of simulation modeling in weed science is several-fold. It provides a means of summarizing data over a range of conditions (e.g., Cousens 1985b), predict results for conditions not covered by experimentation (e.g., Mertens et. al., 2002), suggest optimal strategies for achieving desired results (e.g., Bussan and Boerboom, 2001a), and provide insights into underlying biology and ecology (e.g., Maxwell and Ghersa, 1992). In the instances in which the model presents a successful depiction of reality there is the obvious benefit of predictive capability, but even in the instances in which a given model fails there is a potential benefit, that of a demonstration of areas in which scientific understanding is limited or quantitative inaccuracies exist. In a sense any modeling project can be from start to finish a literature review in a dynamic and workable form, providing insight into appropriate directions for further study.

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Eventually, as a model matures and is successfully validated, it offers the significant promise of augmenting or even replacing field studies which alone could have been financially prohibitive or impossible.

Specifically within the field of weed science the sociopolitical climate surrounding the use of simulation models appears to have been concentrated around three major issues:

1. *There is an increasing concern towards ascertaining the long-term effects of various herbicide programs, crop rotations, and tillage methods.* In particular this concern focuses on the demonstrated reduced efficacy of some herbicides over time, shifts in weed populations which appear to be highly associated with particular agronomic patterns (Webster and Coble, 1997), and the rise of significant populations of herbicide tolerant weed biotypes. In ascertaining the long-term effects the focus is on the development of sustainable agricultural systems, developed from a field of knowledge that is a new merging of conventional agronomic and weed science combined with realistic ecological techniques and principles. (Liebman and Dyck, 1993).

2. *There has been increased pressure among land managers towards a more precise usage of weed control techniques.* Often grouped under the title of 'precision agriculture', this focus is twofold – precision in spatial placement, advocating the use of patch sprayers and other such implements, and precision in temporal placement, which involves the determination of optimal timings of weed

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management events. This focus is driven not only by significant financial pressures to maximize profits with minimal agronomic inputs, but also governmental pressures on growers towards a reduction in herbicide usage (Zoschke, 1994).

3. *There is an increasingly large number of available strategies for weed management, as well as enhanced pressure to ascertain the benefits of using a wider range of alternative strategies in a given weed management plan.* The evaluation of a wide range of possible integrated weed management plans is becoming more common, especially in the context of resistance management in the presence of herbicide tolerant crops such as Roundup Ready™ crops, where the use of crop rotations, different herbicidal modes of action, mechanical weed control methods, and alternative strategies have been implicated as essential to effective long-term management (Hobbs and Humphries, 1995; Beck et. al., 2001).

Each of the above elements describes a variation on the same theme. In order for the field of agronomic research to effectively meet its future demands, the science of weed control will need to explore modes of understanding that are more long-term, systems-based, quantitatively accurate, and predictably consistent. Towards this end, direct field studies are of course always needed, and their direct experimental results are certainly always preferable to simulated results. However, in particular with the third above issue it becomes clear that instances will no doubt exist in which simulated results may need to play a role, with the only alternative requiring an unrealistically large

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number of field studies involving a prohibitively large number of possible treatments over a long period of time. This chapter, as well as the two to follow, describe in detail how this tool has provided such assistance and additional insight into weed population dynamics.

2.2 Types of Models

A set of three relevant distinctions among models has been characterized by France (1988). The first distinction is somewhat trivial, that models can be divided into two classes, dynamic and static, the determining factor being whether or not time is explicitly included in the model. Since weed populations display significant temporal dynamics, the majority of all models developed to-date would fall in the category of 'dynamic', although a derived relationship between weed density and yield loss would most likely serve as the most significant exception.

The second distinction gives insight into the model's origin and level of detail. The two categories are 'empirical' and 'mechanistic'. Empirical models are described as being based exclusively upon experimentally derived, quantitative relationships among a given set of state variables. Usually involving statistical regressions, these quantitative relationships are presented without any further information on any underlying processes in the system. Conversely, mechanistic models make use of such underlying processes, and provide subscale insight into why a given predictive result is occurring. As an

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example, Jasieniuk et. al. (2001) presents and evaluates a series of models that predict winter wheat yield losses as a function of harvest densities of jointed goatgrass (*Aegilops cylindrica*). In each case the models provide direct relationships involving a single equation. These are clear examples of empirical models. In contrast, Dunan et. al. (1999) presents a model that evaluates yield reductions of onion (*Allium cepa* L.) as a function of interactions with weeds as well as multiple environmental variables. Plant growth is evaluated on a daily basis as a function of incident photosynthetically active radiation, leaf area, temperature, interspecific and intraspecific competition, and plant phenology. This would be a good example of a mechanistic model.

It is granted that on a philosophical basis even the most mechanistic models can be understood as being empirical on some level, and, thus, perhaps a clarification of the above definition can be found in stating that mechanistic models characteristically operate in multiple spatial and/or temporal scales, seeking to explain events on the larger scales in terms of processes of the smaller scales (e.g., yield loss is explained above in terms of leaf area and plant competition). Further, the above discussion is not intended to imply a superiority of mechanistic models over equivalent models that are empirical. Indeed, as will be seen later in the discussion of risk assessment (Section 2.4.5), the superior predictive capability may appear in either class.

The last distinction from France (1988) is whether a model is 'deterministic' or 'stochastic', and this is an issue of some relevance in matters of risk assessment. The center of the issue rests upon the degree or manner in which known uncertainties in the

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model's parameters and state variables potentially play a role in the model's results. With a given set of initial conditions deterministic models ignore all such uncertainties and provide a single answer based upon the average values of all variables and parameters, implicitly assuming that such uncertainties neither significantly enhance or mitigate the value of the result. In contrast, the most common form of a stochastic model essentially involves a deterministic model which is executed multiple times, each time with values of parameters and state variables chosen randomly from a given distribution based upon known uncertainties. Instead of providing a single answer, such techniques result in a distribution of answers. Such a technique, though invoked by some previous authors (e.g., Firbank and Watkinson, 1986), in the field of weed science has been comparatively rare, a matter of some contention given the fact that all deterministic models contain an identical implicit assumption, that medium-range values of all state variables and parameters result in medium-range results – in effect, that *the dynamics of the average* are the same as *the average of the dynamics.*

To some extent, however, this methodology and an understanding of its value has indeed made its way into present research in weed science in the form of sensitivity analyses, an insightful component included as part of many otherwise deterministic modeling studies (Bussan and Boerboom, 2001b, Lindquist et. al., 1995b). Thus, it is theorized by the present author that stochastic studies will be on the rise in weed science within the next few years.

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There is a fourth and final distinction that is also on the rise in weed science with the advent of spatially-explicit models which stand in contrast to existing models that consider the spatial area as a single whole. In the field of hydrology this categorization is termed as "lumped" vs. "distributed" models (McDonald, 2003), the latter category being the spatially-explicit ones. More on this will be given in chapter 4.

2.3 Weed Densities and Yield Loss

As has been discussed before, the simulation of weed populations involves numeric comparisons on an economic level. Thus, a working relationship between harvest weed densities and yield loss occupies a position of significant centrality. Not only does it provide a measure of the economic impact of weed populations, but when combined with information on herbicide application and mechanical operation costs it provides the necessary key for evaluating the cost effectiveness of a given weed management strategy.

Some initial definitive work on this subject was done by Cousens (1985a), where a full review was done on all then existing models relating these two quantities. They ranged from simple linear and polynomial relationships to exponential, square root, and hyperbolic functions. Based upon a desire for biologically interpretable parameters and boundary conditions, a hyperbolic equation of the following form was proposed:

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$$y_L = \frac{sAN_w}{1 + sN_w}$$

where y_L is the proportion of yield loss due to weed populations:

$$0 \leq y_L \leq 1$$

(The reader will note that here we are departing slightly from the notation of Cousens, 1985a.) N_w is weed density, and s and A are empirical parameters. It was based upon three desired boundary conditions, the first two simply being that proportional yield losses should be near zero at low weed densities and for high weed densities should approach some constant value:

1. $\lim_{N_w \to 0} y_L = 0$

2. $\lim_{N_w \to \infty} y_L = A$

where

$$0 \leq A \leq 1$$

and a value of 0.7 for A would, for example, indicate a maximum yield loss at high weed densities of 70%. The third boundary condition was an understanding that at low weed densities the relationship between weed density and yield loss should be largely linear:

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3. $y_L = IN_w$

where I represents this linear rate at low weed densities. This is consistent with boundary condition 1. To allow for consistency with boundary condition 2, further increases in weed density are allowed to experience a diminishing return on yield loss, where the per-plant competitive effect of a weed is allowed to decrease as weed density increases. This is done hyperbolically as follows:

$$y_L = \frac{IN_w}{1 + sN_w}$$

where s provides a measure of intraspecific competition in the weed species which would mitigate yield losses. This maximum yield loss can be set thus:

$$\lim_{N_w \to \infty} y_L = \lim_{N_w \to \infty} \frac{IN_w}{1 + sN_w} = \lim_{N_w \to \infty} \frac{I}{\frac{1}{N_w} + s} = \frac{I}{s} = A$$

where we are now able to make use of the parameter A. The equation of Cousens (1985a) for proportional yield loss is, thus, derived:

$$y_L = \frac{sAN_w}{1 + sN_w} \qquad [2.1]$$

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which also appears in the following form:

$$y_L = \frac{IN_w}{1 + IN_w / A} \qquad [2.2]$$

Using the form shown in equation [2.2] a full equation for actual yield Y would be as follows:

$$Y = Y_{wf}(1 - y_L) = Y_{wf}\left(1 - \frac{IN_w}{1 + IN_w / A}\right) \qquad [2.3]$$

where Y_{wf} is the weed-free yield, and again the parameters I and A have the following interpretation:

I: Yield loss per unit increase in weed density, experienced at low weed densities

A: Maximum yield loss for high weed densities

where yield losses in both cases are given in proportion to the weed-free maximum. The form of equations [2.2] and [2.3] is known as 'rectangular hyperbolic.' Numerous studies have been performed in an effort to quantify various crop/weed interference relationships using equation [2.3]. FIGURE 2.1 is an example from Sattin et al. (1992) where the interference between corn (*Zea mays*) and velvetleaf (*Abutilon theophrasti*) was quantified using equation [2.2]. In fact, they utilized an enhancement to equation [2.2] presented by Cousens et al. (1987a):

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$$y_L = \frac{IN_w}{e^{c(t_w - t_c)} + IN_w / A} \qquad [2.4]$$

where the quantity $(t_w - t_c)$ is the relative time of emergence between the weed and the crop expressed in terms of degree days. Such work is echoed by Zanin and Sattin (1988). In corn (*Zea mays*), De Haan et al. (1994) did the same for yellow mustard (*Brassica hirta*), Bosnic and Swanton (1997a) did the same for barnyardgrass (*Echinochloa crus-galli*), Fausey et al. (1997) and Lindquist et al. (1999) did the same for foxtail (*Setaria* spp.), and Knezevic et al. (1994) did the same for redroot pigweed (*Amaranthus retroflexus*).

For soybeans (*Glycine max*), Dieleman et al. (1995) performed the same analysis for the interference of pigweed (*Amaranthus* spp.), and Sartorato et al. (1996) did the same analysis for a variety of weed species, including common lambsquarters (*Chenopodium album*), jimsonweed (*Datura stramonium*), wild proso millet (*Panicum miliaceum*), green foxtail (*Setaria viridis*), black nightshade (*Solanum nigrum*), and common cocklebur (*Xanthium strumarium*). For additional information for such work on soybeans the reader is referred to Stoller et al. (1987).

In cotton (*Gossypium hirsutum*), Askew and Wilcut (2001) did the same for tropic croton (*Croton glandulosus*). The same authors also did similar studies (2002a and 2002b) for Pennsylvania smartweed (*Polygonum pennsylvanicum*) and pale smartweed (*Polygonum lapathifolium*), respectively. Bailey et al. (2003) did the same for velvetleaf (*Abutilon theophrasti*). Bryson (1987) and Rogers et al. (1996) did similar studies for hemp sesbania

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(*Sesbania exaltata*) and ivyleaf morningglory (*Ipomoea hederacea*), respectively, except that the nonlinear relationship between weed density and yield was represented with a quadratic regression and two linear regressions, again respectively. Lastly, Rowland et al. (1999) did a similar study with palmer amaranth (*Amaranthus palmeri*), but the detected relationships were purely linear.

Cousens et al. (1987b) gives a good review of modeling studies in cereal crops, not to mention modeling techniques in general. Most such studies have focused on weeds in winter wheat (*Triticum aestivum*). Such studies have included wild oats (*Avena fatua*) (Cousens et al., 1986), jointed goatgrass (*Aegilops cylindrica*) (Jasienniuk et al., 1999), feryl rye (*Secale cereale*) (Pester et al., 2000), as well as some weeds common to the United Kingdom (Doyle et al., 1986; Lintell-Smith et al., 1999).

Cousens (1985b) also expanded on the above model to allow for changes in crop density:

$$Y = Y_{wf,\max}\left(\frac{N_c}{n_{50,C} + N_c}\right)\left(1 - \frac{IN_w}{1 + IN_w/A}\right) \qquad [2.5]$$

where N_c is the crop density and the weed-free yield parameter Y_{wf} is expanded into a hyperbolic function of crop density. Again the reader will have to excuse the slight change in notation made here to express the above hyperbolic relationship in terms of parameters that have a more straightforward biological interpretation. Here $Y_{wf,\max}$ is the maximum crop yield at the highest crop density. Although understandable only on a theoretical level (yield

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per unit area at infinite crop density), like Y_{wf} before, it can be deduced from real data and has some degree of biological interpretability. Likewise, the parameter $n_{50,c}$ can also be interpreted as the crop density at which yield per unit area reaches half of the value of $Y_{wf,\max}$.

Similarly, Cousens also found that in particular the parameter s varied with crop density. FIGURE 2.2 shows an analysis performed by Cousens on data from Hakansson (1983) showing a hyperbolic decreasing function which Cousens modeled using a sigmoidal curve of the following form:

$$s = \frac{p}{1+qN_c}$$

Ecologically FIGURE 2.2 describes the effect that the first unit change in weed density has on crop yield loss. The figure indicates that that for higher crop densities this initial rate of yield loss is smaller. Expressing this in terms of equation [2.5] this becomes:

$$Y = Y_{wf,\max}\left(\frac{N_c}{n_{50,c}+N_c}\right)\left\{1-\frac{pAN_w}{(1+qN_c)\left[1+\frac{pN_w}{1+qN_c}\right]}\right\}$$

or,

$$Y = Y_{wf,\max}\left(\frac{N_c}{n_{50,c}+N_c}\right)\left(1-\frac{ApN_w}{1+qN_c+pN_w}\right) \qquad [2.6]$$

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where again in the second proportion it is visible that for higher crop densities the same weed density will have a smaller effect on proportional yield loss. FIGURE 2.3 displays the general methodology of Cousens (1985a) and (1985b), where competing models were categorized and evaluated alongside a given data set, in this case involving interference between wheat and barley. As it turned out, the most successful model was a slightly simplified version of equation [2.6], involving two assumptions:

1. The two species are of similar competitive strengths, and, thus, a 100% yield loss from weed populations is possible ($A = 1$)
2. The rate at which additional yield loss per additional weed plant diminishes with increasing weed density is at or close to the rate at which additional yield gain per additional crop plant diminishes with increasing crop density ($q = \frac{1}{n_{50,c}}$).

The two above assumptions affords the following simplification to be made:

$$Y = Y_{wf,\max}\left(\frac{\frac{N_c}{n_{50,c}}}{1+\frac{N_c}{n_{50,c}}}\right)\left(\frac{1+qN_c+pN_w-pN_w}{1+qN_c+pN_w}\right) = \left(\frac{Y_{wf,\max}}{n_{50,c}}\right)\left(\frac{N_c}{1+\frac{N_c}{n_{50,c}}}\right)\left(\frac{1+qN_c}{1+qN_c+pN_w}\right)$$

or,

$$Y = \left(\frac{Y_{wf,\max}}{n_{50,c}}\right)\left(\frac{N_c}{1+qN_c+pN_w}\right) \qquad [2.7]$$

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Thus, equation [2.7] is a simplification of equation [2.6] for a crop-weed combination in which both species are of similar competitive ability. Such may be true for the wheat and barley species utilized in Cousens (1985b), but would certainly not be true for all instances of crop and weed.

The above equations will be seen again, for discussions of yield loss as a function of weed density do not end with Cousens. Jasieniuk et. al. (2001) provides a good example in which three such models are evaluated.

The first such model bears an equivalence to equation [2.5]:

$$Y = \frac{jN_c}{1 + {jN_c}/{Y_{\max}}}\left(1 - \frac{iN_w}{1 + {iN_w}/{a}}\right)$$

where two such hyperbolic functions, one involving crop density N_c and the other weed density N_w, are linked. The other two competing functions were as follows:

$$Y = \frac{aN_c}{1 + bN_c + fN_w} \qquad Y = Y_{\max}\left(1 - \frac{N_w}{bN_c + {N_w}/{a}}\right)$$

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where the first is clearly equivalent to equation [2.7]. The second has no direct equivalency to any previous equations, but bears some resemblance to equation [2.6].

Jasieniuk et. al. (2001) evaluated all models with a variety of datasets according to the success of a nonlinear regression analysis (convergence on a solution, F tests for significance of parameters, satisfaction of regression assumptions, size of SSE, R^2, etc.) as well as overall predictive behavior. The first model on the left showed superior performance to the second on the right, and was deemed the best model of the three for statistical hypothesis testing. However, Maxwell's model was evaluated as being the best model of the three for purposes of estimation.

Although all analyses shown in FIGURE 2.4 made use of one of the hyperbolic relationships previously shown, it should be indicated that other non-hyperbolic models have also been theorized and are displayed in FIGURE 2.5. Also of interest is the fact that in all instances documented in this section, such studies were limited to a single weed species. More on this will be discussed in chapter 4.

2.4 Typical and Atypical Objectives

2.4.1 Economic Optimum Thresholds: "To Spray or Not to Spray"

With the advent of the weed density / crop yield relationships shown above has come the potential of growers and crop consultants to more quantitatively evaluate the seriousness

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of a given weed density, or more to the point, to predict the forthcoming economic losses from observed weed populations. More specifically, weed threshold densities have been calculated above which weed control is deemed desirable. These thresholds have been found to fall into two categories (Swanton et. al., 1999) – 'competitive' and 'economic'. The competitive thresholds tend to be more arbitrary, describing a weed density threshold above which yield losses are deemed unacceptable. Economic thresholds are more precisely calculated, as the threshold level above which the cost of weed control is less than the financial losses of reduced yields from no control. This threshold where these two quantities are the same is referred to as the "economic injury level". Cousens (1997) further extended the above classification into seven categories:

1. *Competition thresholds*, below which weed densities are hypothesized as having no effect upon yield,
2. *Statistical thresholds*, below which weed densities display no statistically detectable effects on yield,
3. *Economic thresholds*, below which the application of a given herbicide or control method does not result in a net increase in profits when the cost of the treatment is included,
4. *Economic optimum thresholds*, at which the implementation of a given threshold decision process produces the most profitable result over the long-term,
5. *Predictive thresholds*, which attempt to aid in decision-making for a given season based upon weed populations in the previous season,

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6. *Safety thresholds*, where weed populations are treated in a probabilistic sense and the threshold defines a weed density based not upon the maximization of profits, but on the guarantee of disaster occurrence from a risk-assessment perspective, and

7. *Visual thresholds*, or intuitive thresholds used by growers to determine what is acceptable.

In the context of a single year the determination of such a threshold is a relatively simple matter and can be solved analytically from the relationships listed in the previous section. The economic return of an herbicide application is defined as follows:

$$P_{return} = P_{herb} - P_{noherb}$$

Simply put, it is the difference in the total profits between spraying and not spraying. The total profits when not spraying have been summarized thus (e.g., Bauer and Mortensen, 1992):

$$P_{noherb} = C_c Y_{wf}\left(1 - y_{L,n}\right) - C_f$$

where C_c represents the price of the crop, Y_{wf} is the weed-free yield, and $y_{L,n}$ is the proportional yield loss from the presence of weeds. In effect the first term is the total gross profit of the sale of the crop, and the second term C_f is simply all of the agronomic operational costs not directly related to weed control (purchased materials, fuel, equipment maintenance and depreciation, rental costs, labor, taxes, etc.) With this in mind, the total profits when spraying does take place are as follows:

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$$P_{herb} = C_c Y_{wf}\left(1 - y_{L,h}\right) - C_f - C_h - C_a$$

where a smaller proportional yield loss $y_{L,h}$ is used, and two new costs are added for the herbicide purchase and application (C_h and C_a, respectively).

The net return is derived from the difference in these two quantities:

$$P_{return} = \left[C_c Y_{wf}\left(1 - y_{L,h}\right) - C_f - C_h - C_a\right] - \left[C_c Y_{wf}\left(1 - y_{L,n}\right) - C_f\right]$$

or,,

$$P_{return} = C_c Y_{wf}\left(y_{L,n} - y_{L,h}\right) - C_h - C_a \qquad [2.8]$$

(This is presented in a different form than that which is in Bauer and Mortensen, but the concept is the same.) As a reminder, here C_c, C_h, and C_a represent the market values (costs) of the soybean crop, herbicide purchase, and herbicide application, respectively, and Y_{wf}, $y_{L,h}$, and $y_{L,n}$ represent respectively the weed-free yield and the proportional yield losses with and without the herbicide application. The first term shows the financial gain of the herbicide, and the last two terms list its costs. With small weed densities the difference in yield losses $y_{L,n} - y_{L,h}$ with and without the herbicide is minimal, and so the first term is small, thus making the latter two terms most significant, showing the herbicide application to not be cost-effective. At sufficiently high weed densities, however, the above difference in

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projected yield losses is large, and when multiplied by the weed-free yield Y_{wf} and then by the price of the crop C_c, creates a gain large enough to offset the cost of herbicide purchase and application. With this in mind, the economic threshold (ET) can be defined as the break-even point between these two regimes, defined as the point where $P_{return} = 0$:

$$P_{return} = C_c Y_{wf} \left(y_{L,n} - y_{L,h} \right) - C_h - C_a \geq 0$$

or, equivalently through algebra:

$$y_{L,n} - y_{L,h} \geq \frac{C_h + C_a}{C_c Y_{wf}}$$

or,

$$y_{L,n} - y_{L,h} \geq \Psi \qquad [2.9]$$

where

$$\Psi = \frac{C_h + C_a}{C_c Y_{wf}}$$

gives an indication of how expensive the herbicide application is, given relative to the maximum (weed-free) gross profits of the crop. Thus, a value of $\Psi = 0.1$ would indicate that the cost of the herbicide treatment takes up 10% of what the gross profits of the crop would be if no weeds were present. It is clear to the point of trivial that for the use of the herbicide to be viable, the value of Ψ must be within the following boundaries:

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$$0 \leq \Psi \leq 1$$

and in fact must be much closer to zero than 1, lest the cost of the herbicide application involve spending too much of the gross profit of the crop.

Bauer and Mortensen (1992) utilize a simple linear relationship between weed density and yield loss:

$$y_{L,n} = IN_w \qquad y_{L,h} = IN_w(1-\varepsilon_H)$$

where ε_H is the herbicidal efficacy:

$$0 \leq \varepsilon_H \leq 1$$

In reference to the third boundary condition of Cousens (1985a) described in the previous section, the above depiction of yield loss implicitly assumes low weed densities. Thus, equation [2.9] becomes:

$$IN_w - IN_w(1-\varepsilon_H) \geq \Psi$$

$$IN_w\varepsilon_H \geq \Psi$$

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$$N_w \geq \frac{\Psi}{I\varepsilon_H}$$

This indicates the threshold density to be:

$$N_{w_HT} = \frac{\Psi}{I\varepsilon_H} \qquad [2.10]$$

Equation [2.10] provides a useful relationship for determining thresholds. In section 2.4 the usage of this equation by Bauer and Mortensen (1992) will be presented.

The expansion of the above analysis to include nonlinear curves between yield loss and weed density makes the above algebra more complex, but solutions can still be found analytically. A full description of this analytical solution process is presented in Appendix A and is presented here in summary form.

According to the convention of Cousens (1985b) presented in the previous section, the yield losses above can be represented thus:

$$y_{L,n} = \frac{IN_w}{1 + IN_w/A} \qquad y_{L,h} = \frac{IN_w(1-\varepsilon_H)}{1 + IN_w(1-\varepsilon_H)/A}$$

where ε_H is the herbicidal efficacy:

$$0 \leq \varepsilon_H \leq 1$$

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and equation [2.9] now becomes:

$$\frac{IN_w}{1+IN_w/A} - \frac{IN_w(1-\varepsilon_H)}{1+IN_w(1-\varepsilon_H)/A} \geq \Psi$$

and solving for the boundaries of the above inequality involves a quadratic equation with the following solution:

$$N_{w,ET} = \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right] \pm \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} \quad [2.11]$$

where the above equation gives the ET, the threshold weed density at which the use of the herbicide with the efficacy ε_H becomes viable. The fact that a "plus-or-minus" (±) symbol exists in the equation indicates that two such solutions exist, which separate three regions of weed density where economic viability must be investigated.

In addition, it is first noticed that in order for the above equation to have any real solutions, the expression under the radical must not be negative:

$$\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H) \geq 0$$

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If the above is less than zero, then mathematically no real solutions exist, and thus no threshold weed density $N_{W,ET}$ exists. From a weed management perspective it is reasonable to assert that such a threshold would cease to exist if the herbicide became so ineffective in controlling the weed that its use was never economically viable. Thus, by setting the above expression greater than or equal to zero we are for the moment seeking to quantify this threshold of herbicidal efficacy at which an ET no longer exists. Solving the above equation for the herbicidal efficacy this becomes:

$$\varepsilon_H \geq \frac{4A\Psi}{(A+\Psi)^2} \qquad [2.12]$$

Thus, there are instances in which no ET is calculable. Equation [2.12] gives a minimum herbicidal efficacy for such a threshold to exist. Returning to our fundamental equation [2.11] for ET, we recall that this involved the solution of a quadratic inequality. The solution to this inequality gives a range of weed densities for which control is financially warranted:

$$\frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] - \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} < N_w < \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] + \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

Since this region is in the middle of two regions for which control is not financially viable suggests that there is not only a minimum density for viability of control, but also a *maximum* density for viable control. Apparently, this maximum threshold describes a point at which weed densities become so high that the yield loss even after using the herbicide is too great to support a crop. If such a result were found to be true for all managerial options, this latter threshold could potentially define the point at which the land would need to

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experience a fallow year (with weed control) or if weed seed production is high enough that weed populations are not reduced in such fallow years that the land would become a financial 'hopeless case' regarding agronomic use. Fortunately, this outer threshold appears to only be a theoretical reality.

Thus, for an ET to exist, the herbicidal efficacy must be above a certain threshold:

$$\varepsilon_H \geq \frac{4\Psi}{(\Psi+1)^2}$$

and the threshold density is defined thus:

$$\frac{-[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H] - \sqrt{[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} < N_w < \frac{-[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H] + \sqrt{[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

where

$$\Psi = \frac{C_h + C_a}{C_c Y_{wf}}$$

We have made a long mathematical journey to explore and quantify an aspect of pest management which is of fundamental importance – the existence of an economic threshold.

O'Donovan and Blackshaw (1997) were able to construct economic thresholds for volunteer barley and field pea. Sartorato et al. (1996) did the same for a variety of weeds in soybeans. In corn (*Zea mays*) and soybeans (*Glycine max*) threshold densities for annual

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broadleaved weeds emerging at the same time as the crop have been determined to be generally less than 5 plants per square meter (Cousens, 1997; Zanin and Sattin, 1988; Weaver, 1986), However, the threshold levels for annual grasses have generally been about an order of magnitude higher – 10 to 40 plants per square meter, as these weeds have been found to be generally less competitive than the broadleaved species.

Numerous other studies with different crop-weed combinations have also been studied, but have unfortunately been found of limited use for two reasons:

1. They have been restricted to instances in which the crop is undergoing competition with only a single weed. More will be discussed on this in chapter 4.
2. Estimates of the empirical parameters involved in calculating these estimates have been found to be highly variable in region and time. Again, more will be discussed on this in chapter 4.

2.4.2 Optimal Products

FIGURE 2.6, from Lybecker et al. (1991), illustrates how a bioeconomic approach similar to that in the previous section was utilized in a decision-making capacity to choose between various herbicides for different agronomic scenarios involving different combinations of grass and broadleaf weeds.

It is worth noting that, although at the time of this writing this has not been observed by the present author in the literature, it would be interesting to invert analyses like the one

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shown above in an effort to assess for each management practice which weed species or combinations thereof would produce the least desirable results. Such an analysis would result in an attachment to any treatment program a listing of its limitations and would be able to alert growers and crop consultants to future vulnerabilities. Such vulnerabilities might include approaching invasive species or herbicide tolerant biotypes.

A notable subgroup to this category would be studies like Bosnic and Swanton (1997b), which explored optimal products in the form of the determination of optimal herbicide rates. This involved a slight modification of equation [2.8]:

$$P_{return} = C_c Y_{wf}\left(y_{L,n} - y_{L,h}\right) - C_h H - C_a$$

where H is the herbicide rate (given as a proportion of the standard rate), and the parameter C_h is specifically the cost of the herbicide when used at the standard herbicide rate.

For the depiction of yield loss they made use of equation [2.4]:

$$y_{L,n} = \frac{IN_w}{e^{c(t_w - t_c)} + IN_w / A} \qquad y_{L,h} = \frac{IN_w\left(1-\varepsilon_H\right)}{e^{c(t_w - t_c)} + IN_w\left(1-\varepsilon_H\right) / A}$$

so that the equation becomes:

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$$P_{return} = C_c Y_{wf} \left[\frac{IN_w}{e^{c(t_w - t_c)} + IN_w / A} - \frac{IN_w (1 - \varepsilon_H)}{e^{c(t_w - t_c)} + IN_w (1 - \varepsilon_H) / A} \right] - C_h H - C_a$$

All that is needed is a relationship between herbicide rate H and herbicide efficacy ε_H. Bosnic and Swanton (1997b) utilized an exponential approach towards maximum herbicide efficacy:

$$\varepsilon_H = \varepsilon_{H,\max} \left(1 - e^{-kH}\right)$$

So that the equation becomes:

$$P_{return} = C_c Y_{wf} \left\{ \frac{IN_w}{e^{c(t_w - t_c)} + IN_w / A} - \frac{IN_w \left[1 - \varepsilon_{H,\max} \left(1 - e^{-kH}\right)\right]}{e^{c(t_w - t_c)} + IN_w \left[1 - \varepsilon_{H,\max} \left(1 - e^{-kH}\right)\right] / A} \right\} - C_h H - C_a$$

and the optimal herbicide rate is the value of H that maximizes P_{return}. FIGURE 2.7a has been generated by the present author utilizing realistic values for glyphosate usage in corn to control giant foxtail (*Setaria faberi*). Such parameter values are displayed in TABLE 2.1.

In addition, results are shown for two different herbicide costs ($8.50 / acre and $30.00 / acre), where again this refers to the cost of the herbicide at the standard rate. These two different herbicide cost values appear as two separate graphs for which profits are displayed as a function of herbicide rate, and different lines refer to different initial weed

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densities. Herbicide rates of maximum profitability are displayed at the locations where the curves reach a maximum. The fact that this optimal rate becomes larger with increasing weed density is observable and confirms the findings of Bosnic and Swanton (1997b).

The aforementioned two authors used the above technique to examine the use of a tank mix of nicosulfuron and rimsulfuron on barnyardgrass infestations in corn to see if in the context of a tank mix rates less than the label rate are favorable. Indeed they found that in many situations greater profits can be made with rates less than the label rate.

FIGURE 2.7b shows the same as FIGURE 2.7a except that for quantifying the relationship between herbicide rate and efficacy a more commonly used log-logistic relationship is utilized (Nielsen et al., 2004; Bussan et al., 2001a):

$$\varepsilon_H = \varepsilon_{H,\max}\left[1 - \frac{1}{1+\left(\frac{H}{H_{50}}\right)^b}\right]$$

The parameters $\varepsilon_{H,\max}$, H_{50}, and b respectively describe the maximum high-rate herbicidal efficacy, the herbicide rate that produces an efficacy of half that of $\varepsilon_{H,\max}$, and an exponential parameter that describes the rate of increase of efficacy as rate increases. These parameter values are displayed in TABLE 2.2.

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Note that in this instance not only is there an optimal herbicide rate that increases with weed density (as before), but there is also a range of weed densities outside of which the usage of the herbicide is never financially viable. This may be due to the fact that in a logistic relationship lower herbicide rates are given a lower efficacy than in a relationship that utilizes an exponential approach.

2.4.3 Optimal Management Timings

If agronomic scenarios were composed of a single weed species emerging at a single moment prior to the emergence of the crop, then the above question of optimal management timings would be trivial. This is, of course, not the case, and the question of choosing such optimal timings requires the following information:

1. A listing of what weed species are present,
2. An understanding of when such weed species are going to emerge, and
3. A quantitative understanding of when in the growing season crop plants are vulnerable to the effects of weed competition.

The first element above makes the argument for effective modeling of multiple weed species in the same system. This will be discussed more in chapter 4. The second provides reasoning for the large arena of research devoted to predicting weed emergence patterns. For more information on this see chapter 3.

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The third and last element defines what is referred to in the literature as the 'critical period' for weed control. Equation [2.4] from Cousens et al. (1987a) defines an initial quantitative methodology for doing so. Experimentally this information is generally found in one of two ways:

1. Yield loss for a given weed density is quantified in relation to time of weed emergence, or
2. Yield loss for a given weed density is quantified in relation to time of weed removal.

FIGURE 2.8 from Bosnic and Swanton (1997a) shows corn yield loss relationships to barnyardgrass density for four different combinations of site and year. Each graph contains two lines, one for each of two different emergence times for barnyardgrass. In most plots it is visible that barnyardgrass emerging at a later time in the season (dashed lines) has a considerably smaller effect on yield. This strong dependence on relative time of emergence between the crop and weed (independent of a dependence on weed density) has been confirmed by multiple authors in corn (Sattin et al., 1992; Strahan et al. 2000; Mickelson and Harvey, 1999), soybeans (Crook and Renner, 1990; Dieleman et al. 1995; Stoller et al., 1987), and winter wheat and barley (Cousens et al., 1987a; Blackshaw, 1993; Anderson, 1993). FIGURE 2.9 from Cousens et al. (1987a) shows how this relative time of emergence plays a role comparable to that of weed density. Again, the associated equation for yield is:

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$$Y = Y_{\max}\left[1 - \frac{IN_w}{e^{c(t_w - t_c)} + IN_w / A}\right] \qquad [2.15]$$

Similar equations have been used by Mickelson and Harvey (1999):

$$Y = \frac{Y_{\max}}{e^{k(t-t_0)}} + Y_{\min} \qquad Y = ae^{-be^{-k(t-t_p)}}$$

Such findings have many unexplored implications. Hoffman et al. (2002) have begun to explore management practices that would give sorghum an earlier emergence timing, resulting in a competitive advantage over weeds. Also of interest is the fact that such studies begin to bridge the chasm between empirical models and the more mechanistic daily growth models by giving indications of when crop plants are vulnerable. For example, from equation [2.15] the derivative of Y with respect to timing of weed emergence:

$$\frac{dY}{dt_w} = Y_{\max}\frac{cIN_w e^{c(t_w - t_c)}}{\left[e^{c(t_w - t_c)} + IN_w / A\right]^2}$$

gives an initial indication of this timing of crop vulnerability. As an example, FIGURE 2.10 has been generated by the present author, showing applications of equation [2.16] to the results of Cousens et al. (1987a) for wheat and barley. In this figure the concept of a 'critical period' of weed control is especially visible and appears to not only be a longer period of time for wheat than barley, but also appears to exhibit a dependence on weed density.

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FIGURE 2.11, from Sattin et al. (1992) shows another application of such findings – the calculation of the extent to which ET depends upon this relative emergence timing. The figure illustrates again that control is most critical for early emerging weeds.

2.4.4 Long-Term Planning

Implicit in the directive towards a more ecological and sustainable approach to agriculture is the desire for a management approach that focuses on long-term effects. Such an approach has many components, including the preservation of soil organic matter, the conservation of groundwater, the preservation of the environment, and the prevention of herbicide tolerant weed populations. Thus, although aspects of weed control only play a partial role in such a long-term vision, its role is not wholly absent, and is exemplified most conspicuously in the modeling of herbicide tolerance in weeds. More on this in section 3.5.

In addition, however, has come the evaluation of the efficacy of different control methods in terms of a multi-season rubric, where net profits were compared for different treatment methods not only over a single cropping season, but over multiple cropping seasons. This was first done by King et al. (1986) and is presented in terms of the economic notation first introduced in section 2.4.1:

$$P_{jk} = C_c Y_{wf}\left(1 - y_{L,h}\right) - C_f - C_h - C_a$$

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where the subscripts on profit denote net profit for the j^{th} rotation or treatment program implemented in the k^{th} cropping season. For a given rotation or treatment program, the net profits are summed over all seasons in the planned time span:

$$P_{j.} = \sum_{k=1}^{m} P_{jk} w_k$$

where w_k is a weighting function that allows for profits in earlier years to be weighted more due to the fact that they have more years to compound interest. The derivation of this weighting function begins with the following expression which defines the amount of interest accrued from a single annual compounding of the profits for the j^{th} rotation or treatment program implemented in the k^{th} cropping season:

$$iP_{jk}$$

where i is the annual interest rate. This can also be written as:

$$[(1+i)-1]P_{jk}$$

After k years of compounding the total amount of interest accrued would be:

$$\left[(1+i)^k - 1\right]P_{jk}$$

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and so the ratio of accrued interest after k years to accrued interest after one year would be:

$$\frac{(1+i)^k - 1}{i}$$

Presumably to avoid numerical instabilities, instead of scaling up the profits in the earlier years, the weighting function scales down the profits in the later years, thus involving the reciprocal of the above expression:

$$w_k = \frac{i}{(1+i)^k - 1} = \frac{i}{1-(1+i)^{-k}}(1+i)^{-k}$$

Thus, the final expression is as follows:

$$P_{j.} = \sum_{k=1}^{m} P_{jk} w_k = \sum_{k=1}^{m} \frac{i}{1-(1+i)^{-k}} P_{jk}(1+i)^{-k}$$

which is of the form presented in King et al. (1986). It is essentially a weighted average with the addition of a single parameter, an annual interest rate.

2.4.5 Risk Assessment

Economic decision-making within agronomic weed management is not without some degree of predictive uncertainty. Equation [2.8] describes many processes that are subject to

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variation, either as a result of environmental variance (e.g., yield loss or maximum weed-free yield) or economic fluctuation (e.g., crop price or herbicide cost). FIGURE 10a from Zanin et al. (1992) shows one aspect of this variation, where a series of repeated field experiments of various weeds in different crops resulted in some probability distributions of yield loss in the absence of weed control (y_{Ln}). The figure shows such results for soybeans (top) and sugarbeets (bottom). In the absence of any variability in other variables or parameters, such graphs can be used to obtain similar probability distributions for P_{return}, where a given grower or crop consultant can be given not merely a single decision-making answer, but a distribution of possible answers, including a probability of positive economic return. Although this stage of decision-making in weed science is yet to be achieved, such a presentational format is highly compatible with common managerial language of large-scale growers (Nissen, personal communication) and is a style of evaluative decision-making well understood in other branches of financial management (Koller, 2000).

2.5 The Exponential and Logistic Equations

In addition to the biology and economics of weed management, it is of some value to also focus on the intrinsic dynamics of the weeds themselves. The most simplistic representation of such dynamics would be as follows:

$$N_{t+1} = \lambda N_t$$

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where N_t represents the population of a given weed species at time t. The parameter λ is usually referred to as a 'growth rate', and if its value were known for every weed species in every cropping system in any given set of environmental conditions, all simulation efforts would end here. That is, of course, not the case. The growth rate of a given weed species is known to be a highly complex function of seed bank processes, seed viability, processes of competition involving emergence patterns, weed and crop density, phenology, and spatial arrangement, as well as processes of fecundity that involve seed production and degree of spatial dispersal. All of this is then combined with the efficacies of various weed control techniques as well as some additional undesirable effects of such techniques (e.g., the dispersal of weed seeds by tillage equipment) to make what may be considered as a full description of the variation of λ.

The process of representing as many of the above processes as possible in any weed dynamics model involves, of course, an abandonment of the above equation in favor of a more mechanistic approach. Here, however, it is perhaps of some significance to correct a common intuitive misunderstanding – that is, the transition from an empirical approach to a more mechanistic one is not always a descent into the relative unknown. In fact, in the case to follow it is rather an embrace of what is more fully known. Accurate knowledge may not exist of the degree to which the growth rate λ of a given weed species is changed by the application of an herbicide, but it is more accurately known the extent to which such an application will eradicate existing emerged weeds as well as curtail the seed production and seed viability of subsequently emerged weeds in the season.

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An assumption that λ is constant results in the simple exponential growth model, which is fully derived thus. Using a Taylor series expansion (Stein, 1987) N_{t+1} is represented in terms of N_t:

$$N_{t_0+\Delta t} = N_{t_0} + \Delta t \left.\frac{dN}{dt}\right|_{t_0} + \frac{(\Delta t)^2}{2!}\left.\frac{d^2N}{dt^2}\right|_{t_0} + \frac{(\Delta t)^3}{3!}\left.\frac{d^3N}{dt^3}\right|_{t_0} + \cdots$$

$$\approx N_{t_0} + \Delta t \left.\frac{dN}{dt}\right|_{t_0}$$

This, combined with the equation involving the growth rate becomes:

$$\lambda N_{t_0} \approx N_{t_0} + \Delta t \left.\frac{dN}{dt}\right|_{t_0}$$

or,

$$\Delta t \left.\frac{dN}{dt}\right|_{t_0} = (\lambda - 1)N_{t_0}$$

Dividing all terms by N_{t_0} this becomes:

$$\Delta t \left.\frac{d \ln N}{dt}\right|_{t_0} \approx \lambda - 1$$

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Moving dt to the other side and integrating from t_0 to t time steps, $t(\Delta t)$, forward this becomes:

$$\Delta t \int_{N_0}^{N_t} d \ln N \approx \int_{t_0}^{t_0 + t(\Delta t)} (\lambda - 1) dt$$

$$\Delta t \ln\left(\frac{N_t}{N_0}\right) \approx t(\Delta t)(\lambda - 1)$$

$$N_t \approx N_0 e^{(\lambda - 1)t} \qquad [2.16]$$

where the approximation symbol $\approx$ indicates the error associated with the finite time steps (Δt) involved in numeric integration. Increasing populations are represented by values of λ that are greater than 1, and decreasing populations by values of λ that are less than 1.

Of course, since weed populations cannot explode to infinity the way that the above exponential function can, initial attempts to include density dependence involved the addition of a maximum density K, often referred to as the 'carrying capacity'. What resulted were what is known as the logistic growth models, the most popular of which can be derived as follows:

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With the growth rate now being taken as variable, the constant λ can now be thought of as the initial growth rate, or theoretically speaking the growth rate at zero density. Similarly, the growth rate when the density has reached the carrying capacity is taken to be zero.

Thus, we have two points:

$$\left.\frac{dN}{N}\right|_{N_i=0} = \lambda \qquad \left.\frac{dN}{N}\right|_{N_i=K} = 0$$

and, according to the following Taylor series expansion:

$$N_{t_0+\Delta t} = N_{t_0} + \Delta t \left.\frac{dN}{dt}\right|_{t_0} + \frac{(\Delta t)^2}{2!}\left.\frac{d^2N}{dt^2}\right|_{t_0} + \frac{(\Delta t)^3}{3!}\left.\frac{d^3N}{dt^3}\right|_{t_0} + \cdots$$

$$\approx N_{t_0} + \Delta t \left.\frac{dN}{dt}\right|_{t_0}$$

the quantity $\frac{dN}{N}$ can be approximated thus:

$$\left.\frac{dN}{N}\right|_{t_0} \approx \frac{N_{t_0+\Delta t} - N_{t_0}}{N_{t_0}}\frac{dt}{\Delta t} \approx \frac{N_{t_0+1} - N_{t_0}}{N_{t_0}}$$

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where it has been assumed that the time step Δt is small enough that it can be taken as a differential dt and that higher-order differential properties are negligible. Thus, we now have the following two relationships:

$$\left.\frac{N_{t+1}-N_t}{N_t}\right|_{N_t=0}=\lambda \qquad \left.\frac{N_{t+1}-N_t}{N_t}\right|_{N_t=K}=0$$

and, assuming that the quantity $\frac{N_{t+1}-N_t}{N_t}$ varies in a linear fashion with N_t between these two boundaries[1], we can create the following convention:

$$\frac{N_{t+1}-N_t}{N_t}=mN_t+b$$

where we are postulating the presence of a slope and y-intercept $(y=mx+b)$. The y-intercept is indicated immediately by the value of the expression for $N_t=0$. It is λ. The slope can be determined via the following:

$$\frac{0-\lambda}{K-0}=-\frac{\lambda}{K}$$

Thus, our equation becomes:

[1] This is a highly questionable assumption, but a valid beginning, and it is implicit in the most popular form of the logistic growth equation.

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$$\frac{N_{t+1}-N_t}{N_t} = mN_t + b = -\frac{\lambda}{K}N_t + \lambda = \lambda\left(1-\frac{N_t}{K}\right)$$

or,

$$N_{t+1} = N_t + \lambda N_t\left(1-\frac{N_t}{K}\right) = N_t + \lambda N_t\left(\frac{K-N_t}{K}\right)$$

Setting $\beta = \frac{\lambda}{K}$ an equivalent form also found in the literature can be derived:

$$N_{t+1} = N_t + \lambda N_t\left(1-\frac{N_t}{K}\right) = N_t + \lambda N_t\left(1-\frac{\beta N_t}{\lambda}\right) = N_t + N_t(\lambda - \beta N_i)$$

$$N_{t+1} = N_t[(\lambda+1) - \beta N_t] = N_t(\alpha - \beta N_t)$$

where the parameter β controls the density-dependence and $\alpha = \lambda + 1$. Although based upon rudimentary assumptions, even these logistic equations have been demonstrated to display oscillatory and even chaotic phenomena (May, 1976).

In the above equations an important assumption is made, here displayed in two equivalent forms in FIGURE 2.12. Simply put, the assumption is that with an increase in the population the growth rate decreases in a linear fashion. On a biological level this may be equivalent to stating that with an increase in the population the available resources decreases

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in a linear fashion. From the discussion in section 2.3 it is reasonable to assert some doubt here, but to nevertheless recognize this, again, as a valid beginning.

Recalling a form of our equation from before:

$$\frac{N_{t+1} - N_t}{N_t} = \lambda - \beta N_t$$

Vandermeer (1981) described a different form of the logistic equation, one which allowed for an asymptotic buffering of this growth rate reduction:

$$\frac{N_{t+1} - N_t}{N_t} = \frac{1}{f(N_t)}(\lambda - \beta N_t)$$

where it was found that an appropriate form for $f(N_t)$ is:

$$f(N_t) = 1 + aN_t$$

since when the population N_t is zero, then $f(N_t) = 1$, and so in the denominator it produces no effect. As N_t increases, however, it buffers the reduction in the growth rate, resulting in a curvilinear response. Thus, the equation becomes:

$$\frac{N_{t+1} - N_t}{N_t} = \frac{\lambda - \beta N_t}{1 + aN_t}$$

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where there are now two parameters describing density dependence.

These equations, although suitable for displaying some fundamental introductory weed population dynamics, have been used only to a limited extent in the majority of recent studies in weed science, primarily due to the fact that, although processes of growth and density-dependence are included in the above equations, processes of herbicide application and other weed control practices are not easily applied to the above formulas. Thus, these relationships greatly lack any degree of applicability and are usually only discussed in purely academic contexts. In its wake one is reminded of an important philosophical aspect of any kind of mathematical simulation, that the structure of any given model is largely determined by the following three elements:

1. The desired quantities for simulation
2. The nature of available data
3. The desired processes for inclusion

In the present case, the desired quantities of simulation are weed densities and yield loss, thereby underscoring the significance of our initial equations relating these two quantities. The second aspect, the nature of the available data, was discussed during the analysis of the exponential equation – i.e., the available research findings are not in the form of growth rates. In our latter instance with the logistic equations the importance of the third

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element is illustrated, as all-important processes of weed control are not easily represented although complex dynamics are beginning to become visible.

Thus, it is concluded here (as well as implicitly by many other sources) than an effective 'real-world' weed shift model will in most cases require a more explicit depiction of plant processes.

2.6 Initial Depictions of Plant Process

As is illustrated by FIGURE 2.13, on a most fundamental level, annual plants emerge from seeds, grow, set seed, and die. (Biennials and perennials will be discussed in chapter 3.) Thus, the explicit depiction of plant process can in many instances be reduced to five demographic processes:

1. Emergence of a known number of seedlings as a function of number of seeds in the seed bank,
2. The survival of seedlings to mature plants,
3. The seed production of the mature plants,
4. The dispersal of the new seeds, and
5. The survival of seeds in the seed bank.

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To begin this analysis, the focus will be initially placed on corn (*Zea mays*) and soybeans (*Glycine max*), two agricultural systems commonly placed in rotation with each other. Some common weed problems in these cropping systems are wild oats (*Avena fatua* and *Avena sterilis*), barnyardgrass (*Echinochloa crus-galli*), redroot pigweed (*Amaranthus retroflexus*), common sunflower (*Helianthus annus* and *Helianthus petiolaris*) and velvetleaf (*Abutilon theophrasti*).

Lindquist et. al., (1995a) conducted a series of field experiments in 1992 and 1993 in an effort to quantify each of the above listed demographic processes for velvetleaf in soybean. FIGURE 2.14 shows an example of this, where emergence was calculated via regressions of total seasonal emergence on the spring seed bank. A simple linear regression sufficed, and an emergence proportion of 0.068 was calculated. Percentage emergence was also measured as a function of time and growing degree days.

Seedling survival was also measured, and in particular in 1993 appeared to be strongly curtailed by the presence of soybean. Seedling survival was also curtailed by the presence of *Verticillium dahliae* infection. Seed productivity was also strongly curtailed by the presence of soybean. Soybean yield was not reduced by velvetleaf density, but this may have also been largely the result of the *Verticillium* infection. Soybean yield was found to increase with soybean density (decreasing row spacing) in a fashion which was represented by a hyperbolic function of the form proposed by (Cousens, 1985b) and discussed earlier.

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Seed bank survival was calculated as the result of two measurements – a regression of the August seed bank on the spring seed bank, and a regression of the following year spring seed bank on the autumn seed bank, the product of which provided a measurement of seed bank survival.

Work such as this is widely apparent and strongly supports the kind of modeling efforts exemplified by the following triplicate of studies, which will now be comparatively examined in detail:

1. Bauer and Mortensen (1992). A model for velvetleaf and common sunflower in soybeans,
2. Gonzalez-Andujar and Fernandez-Quintanilla (1991). A model for Avena sterilis in corn, and
3. Bussan and Boerboom (2001b). A model for velvetleaf in a corn/soybean rotation.

Throughout this trio of studies, a consistent notation will be used:

S_t : Seed bank population in year t

G_t : Seedling numbers in year t

$N_{t,i}$: Populations of mature plants in year t surviving treatment i

R_t : Numbers of seeds in the seed rain in year t

ε_H : Efficacy of herbicide use in weed control

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ε_T : Efficacy of tillage operations in weed control

μ : Either weed or seed mortality (indicated more fully by a subscript)

Bauer and Mortensen (1992) simulated its weed populations in the following manner:

Their depiction of emergence was the most complex part of the model. A study by Burnside et. al. (1981) had empirically quantified the degree to which seeds of various species germinate as a function of years in the seed bank. A rectangular hyperbola of the following form was used:

$$g_i = \frac{a}{i+b}$$

where g_i is the proportion of seed germinated after i years in the seed bank. The parameters a and b were empirically determined for a series of weed species, and these data were used in the simulation at hand. The calculation of total germinated seed in year t involving summing over all ages of weed seed was:

$$G_t = \sum_{i=1}^{n} g_i S_{t,i} = \sum_{i=1}^{n} S_{t,i} \frac{a_w}{i+b_w}$$

where $S_{t,i}$ is the number of seeds of age i in the seed bank in year t, and the summation is done up to a maximum age of n years. The number of seedlings was defined as the number of these new germination events which also survived an early tillage event:

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$$N_{t,1} = (1-\varepsilon_T)G_t = (1-\varepsilon_T)\sum_{i=1}^{n} S_{t,i}\frac{a_w}{i+b_w}$$

and the number of mature plants as those seedlings which survived a post-emergence herbicide treatment:

$$N_{t,2} = (1-\varepsilon_H)N_{t,1}$$

(Implicit in this is the assumption of 100% survival in the absence of any weed control.) For seed production constant fecundity values were used:

$$R_t = fN_{t,2}$$

which were 4300 seeds per plant for velvetleaf and 7750 seeds per plant for sunflower. The predation of this new seed rain was also considered as constant, and so the addition of new seeds to the seed bank was treated as follows:

$$S_{t+1,1} = (1-\mu_R)R_t$$

where μ_R is the overwintering seed rain mortality, and the annual mortality of seeds in the seed bank was also considered as constant:

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$$S_{t+1,i+1} = (1-\mu_s)S_{t,i}$$

where μ_s is the annual seed bank mortality.

As a result of the above analysis, EOT's were calculated for each weed in soybeans. Again, such a threshold is defined as the level of weed infestation at which the application of an herbicide becomes cost-effective. This analysis proceeded according to the same theoretical development as that explained in section 2.4.1, except that the yield loss equation ignored intraspecific competition among the weeds. Thus, the calculation of EOT would have followed the form of equation [2.9] except that it involved a long-term scope, thus lifting the assumption that the only economic influence of a given weed density is in crop yields in the present season. Of course, by setting seed, weed populations have an indirect effect on crop yields in subsequent seasons as well. Thus, a clear use for simulation modeling is indicated, and the authors simulated weed populations over a course of fifteen years, each time with different values of the economic threshold N_{EOT}. Profits were tallied, and optimal long-term values of N_{EOT} were acquired. Thus, the biological portion of the present model can be summarized by TABLE 2.3, where descriptions are provided to the right of each modeling aspect.

For velvetleaf in soybean this long-term EOT was estimated to be between 0.3 and 0.4 plants per 10 m^2 area. The same value for sunflower was estimated to be 0.4 plants per 10 m^2 area.

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Next considering Gonzalez-Andujar and Fernandez-Quintanilla (1991), a similar model was created for the depiction of the population dynamics of *Avena sterilis* in corn.

Two periods of emergence were considered, where the number of seedlings emerging in year t for each emergence period j are:

$$G_{t,j} = \alpha_j S_{t,j}$$

where α_j is the emergence proportion for emergence period j. Such values had been obtained experimentally and are known with standard errors as well. Seedling survival to mature plants is presented with direct density-dependence for each cohort:

$$N_{t,j} = \frac{G_{t,j}(1-\varepsilon_j)}{1+a_j G_{t,j}}$$

where ε_j allows for a weed control efficacy to be placed on cohort j. Again, the parameter a_j is also deduced empirically.

Seed production is also presented with a direct density-depdendence:

$$R_t = \sum_{j=1}^{2} \frac{\phi_j N_{t,j}(1-\mu_o)}{1+b_j N_{t,j}}$$

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where the parameters s_j and b_j have also been deduced empirically, and μ_o represents an overwintering mortality. Lastly, the seed bank dynamics are modeled thus:

$$S_{t+1} = S_t \prod_{k=1}^{3}(1-\mu_{s,k}) \prod_{j=1}^{2}(1-\alpha_j) + R_t$$

where an allowance is made to mortality over three periods and losses to two emergence periods.

Thus, a summary of this model makeup is displayed in TABLE 2.4, where two validation tests were conducted, one with a wild oat herbicide applied to a continuous crop of winter wheat, and the other in a fallow-spring barley rotation with no herbicide application. In each case, although quantitatively there was some disagreement, qualitatively the results matched.

The model runs indicated that:

1. An 85% control was necessary to effectively eradicate weeds over the long term
2. Winter-acting herbicides which eliminated the first cohort were more effective in long-term weed eradication. The second cohort plays a relatively minor role in overall population dynamics.

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3. The inclusion of a fallow year with appropriate tillage is particularly effective in controlling *A. sterilis*, particularly because in the fallow year the wild oats plants are all practically destroyed before they have the opportunity to set seed.

4. To reduce populations over the long-term it becomes necessary to combine crop rotation with herbicide application. For continuous cropping systems, even annual applications of herbicides employing 80-90% control will result in only a containment of the population.

In particular the fourth finding again illustrates an important aspect of the benefits of modeling studies, that with so many management options available to agricultural land managers today, a modeling study allows for the investigation of some if not all of the possible combinations of each entity of choice, a benefit which in an experimental context presents oftentimes prohibitive logistic and financial challenges. In this study, it was found that the effective management of *Avena sterilis* in corn required the combined use of herbicides as well as a rotation involving either fallow or fallow and spring barley.

What is also significant about this model, in the context of the other two as well as in general, is that it represented the first effort to effectively model a weed over two emergence periods. With this in mind, the finding that the first weed cohort is the most significant contributor to the overall dynamics is a non-trivial discovery when it comes to effective weed management.

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Lastly, given the fact that many of the experimentally-derived parameters in this model contained standard deviations, it may have been of some use to make the model stochastic, allowing for results to be presented in the form of a range. Such results may have been more insightful when it comes to the model validation portion. A comment is made at the end of the paper to this effect. This will be done more explicitly with the third and last model.

The model of Bussan and Boerboom (2001b) was created for the purpose of simulating the effect of herbicide, tillage practices, and wilt disease (*Verticillium dahliae* Kleb.) on the population dynamics of velvetleaf in a rotation of corn and soybeans. The simulation was long-term (20 years) and involved not only calculations of economic optimum thresholds (EOT), but also annualized net returns (ANR), which will be similarly defined in a moment.

In many ways the model is very similar to those considered before. Seedling emergence was calculated thus:

$$G_t = \alpha S_t$$

where α is completely constant at (0.068) and the seed bank was uniform in depth. Mature plant density was calculated thus:

$$N_t = G_t(1-\mu_g)(1-\delta\varepsilon_{T,r})(1-\varepsilon_H)$$

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where μ_g is the mortality rate of seedlings and $\varepsilon_{T,r}$ is the efficacy of applying mechanical treatments in crop r. Both parameters were held constant. The variable δ was set to zero or one, depending on whether or not mechanical treatments were included or not. The herbicide efficacy ε_H was allowed to vary in response to herbicide rate:

$$\varepsilon_H = \varepsilon_{H,\max} - \frac{\varepsilon_{H,\max} - \varepsilon_{H,\min}}{1 + \left(\frac{H_{50}}{H}\right)^b}$$

This represented one of the most significant explicit aspects of the model – it allowed for variable herbicide concentrations to be attempted. The above equation defined an herbicide mortality rate derived from a sigmoidal dose response curve. Here z represents the herbicide dose (usually expressed as a fraction of the recommended dose – 1X, ¼ X, 2X, etc.) z_{50} represents the herbicide dose rate resulting in 50% control, $\mu_{H,\min}$ and $\mu_{H,\max}$ showed respectfully the minimum and maximum herbicide morality rates, and b is an empirical parameter. In addition, different values of such parameters were also calculated in the presence of an infectious agent which is damaging to the velvetleaf, *Verticillium dahliae*. Thus, this work echoes some of the philosophical elements discussed earlier on, namely how present modeling work has been influenced by a desire for integrated management involving the reduction of herbicide usage and the embrace of alternative management methods like the introduction of bio-control agents.

Seed rain was calculated thus:

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$$R_t = \phi N_t e^{-\beta N_t}$$

where ϕ describes fecundity or per capita seed production, and β describes the rate of exponential decline of per capita seed production with increasing density. As the highlight indicates, the two parameters were not constant, but in some cases were presented as functions of herbicide rate, according to an equation of the same form as that for herbicide efficacy:

$$\phi = \phi_{\min} + \frac{\phi_{\max} - \phi_{\min}}{1 + \left(\frac{H_{50}}{H}\right)^b}$$

In particular the addition of a dependence on herbicide rate to the seed production equations were the result of previous studies which indicated that velvetleaf escapes produced more seed per plant when herbicide rates were low than when the rates were high.

Updating of the seed bank involved calculating the survival of the nonemerged seeds as well as the survival of the new seeds from the seed rain:

$$S_{t+1} = (1-\mu_s)(1-\alpha)S_t + (1-\mu_o)R_t$$

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where μ_b and μ_s represent the mortality rates of seeds in the seed bank and the overwintering seed rain, respectfully. Again, both were constant. Velvetleaf biomass was also calculated via:

$$B_t = \widetilde{\beta}_1 N_{m,t} e^{-\widetilde{\beta}_2 N_{m,t}}$$

where $\widetilde{\beta}_1$ and $\widetilde{\beta}_2$ describe the average biomass per plant and the rate of exponential decline in biomass per plant with increasing plant density. Again, both parameters were allowed to vary in response to herbicide rates. Yield loss was listed as a linear function of weed biomass:

$$Y_{L,t} = \eta B_t$$

and net return was calculated based on total yield minus herbicide costs, herbicide application costs, and mechanical treatment costs:

$$P_t = Y_{\max}\left(1 - Y_{L,t}\right)p - rC_h - C_a - qC_m$$

where $Y_{\max}$, p, r, C_h, C_a, C_m, and q represent respectfully, the maximum (weed-free) yield, the crop price, the herbicide application rate, the herbicide cost, the herbicide application cost, the cost of mechanical treatments, and a variable that is either zero or one depending on whether or not mechanical treatments were utilized.

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Thus, the biological portion of the model can be summarized in TABLE 2.5. Lastly, annual net return was calculated from the following equation:

$$P_{an} = \left[\sum_{t=1}^{n} P_t (1+I)^t\right]\left[\frac{I}{1-(1+I)^{-t}}\right]$$

where the interest rate I was set to 0.04. Originally used by King et. al. (1986), it allows for the values of profits in different years to be differentially weighted in response to a constant interest rate. EOT was calculated via repeated runs of the model to determine for a given initial seed bank size or seedling density what herbicide application rate maximized Pan. In addition, sensitivity analyses were conducted according to the following equation for a given parameter γ:

$$Q = \frac{\Delta EOT / EOT}{\Delta \gamma / \gamma}$$

where Q is the measure of sensitivity for the parameter γ.

Since initial seed bank density only had a quantitative effect on the results, but not a qualitative effect, the model runs shown were all made with the same initial seed bank density. Untreated velvetleaf showed a hyperbolic response, implying a density-dependent regulation. Seed bank response was undifferentiated from this untreated response for herbicide applications less than 1/8 X with or without mechanical treatment. Herbicide

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applications of ¼ X reduced seed production but not enough for effective management. Herbicides at ½ X rates with and without mechanical treatment reduced the velvetleaf seed bank by 95% in 11 and 20 years, respectively. Herbicides at 1X rates reduced the seed bank by the same amount in 6 years, with our without mechanical treatment. This degree of decline for the 1X rate was similar to previous simulation results (Lindquist et. al., 1995b) but was faster than some previous studies of long-term velvetleaf management. This study shows a contrast to similar studies involving *Setaria faberi* which showed equally proficient management with herbicides at 1X and herbicides at ½ X with mechanical treatment (Bussan and Boerboom, 2001a; Bussan and Boerboom, 2001b). The difference is thought to be attributed to velvetleaf's greater survival and seed production under lower herbicide application rates.

Wilt only had an effect on *Abutilon theophrasti* seed banks when the probability of infection was greater than 50%. At 100% infection the effect was similar to that of the 1X herbicide rate. There was little or no difference in the response between seed banks from velvetleaf with wilt and a 1X application and those from velvetleaf with the 1X application alone. However, with a 50% chance of wilt infection only a ½ X application rate was necessary to reduce seed banks by 95% in less than 10 years. With a ¼ X application rate and chances of infection at 50% and 75% the time for a 95% seed bank decrease was 20 and 13 years, respectively.

For seed banks of 10, 100, and 1000 seeds / m^2 ANR was maximized at 3/8, 7/16, and 5/8 application rates, respectfully. These rates were reduced with the inclusion of wilt.

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EOT values were also calculated for the optimal minimum seedling densities for herbicide application. This was maximized at 0.55 seedlings / m^2 but varied little between 0.4 and 0.7 seedlings / m^2 at the 1 X rate. At the ½ X rate this maximum was 0.4 but did not vary between 0.1 and 1.0 seedlings / m^2. These levels increased with the inclusion of wilt.

Parameters displaying the highest sensitivity were emergence proportion, seedling mortality, seed bank survival, overwinter survival of seed rain, and all dose-response parameters associated with seedling survival and seed production.

Considering all three studies together, one finds overall similarities, but in particular different areas of explicit consideration. All three models are long-term weed dynamics models involving essentially the same 'family' of crops and annual weeds. However, there are differences. Bauer and Mortensen's model is comparatively simplistic with the exception of the seed bank depiction. Gonzalez-Andujar and Fernandez-Quintanilla's model ignores such an explicit seed bank representation and instead focuses primarily on density-dependence and the explicit representation of two weed cohorts. Bussan and Boerboom's model ignores the presence of multiple cohorts and instead focuses on the implications of bio-control as well as the effect of variable herbicide rates on survival, seed production, and biomass. It has been stated that "all models are wrong, but many are useful". No doubt a consummate simulation model involving all aspects of the dynamics of the above cropping systems would involve an amalgamation of all processes represented explicitly in the above models. However, it is not to be concluded that the inclusion of all such processes is

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necessary in all instances. Gonzalez-Andujar and Fernandez-Quintanilla's work, by not including an explicit age-descriptive seed bank depiction, simply contains an implicit assumption that for modeling the long-term dynamics of *Avena sterilis* in corn seed bank populations play an important role, but seed bank *ages* do not. This is an assumption that can be evaluated both experimentally and mathematically. In the same way Bussan and Boerboom's model implicitly assumes that in evaluating the use of variable herbicide rates and *Verticillium* infection to control velvetleaf in corn and soybeans, the explicit consideration of multiple weed cohorts is unnecessary, an assumption that appears to be intuitively reasonable.

It is true that in some cases a lack of explicit consideration is reflective of an absence of data – Bussan and Boerboom's data on the effects of herbicide rate were not available at the time of Bauer and Mortensen's work, and, thus, in this instance Bussan and Boerboom's model is to be considered an improvement over that of Bauer and Mortensen.

There are numerous other studies which bear a strong resemblance to these three examples. The study of Firbank and Watkinson (1986) can be summarized in TABLE 2.6, where note that separate equations exist for modeling the crop and the weed. Also, here S is a crop sowing rate, and ε implicitly describes the efficacy of any and all control measures.

Note also that the seed 'bank' here does not act as a bank at all. It was known that non-germinating seeds did not persist in the soil, and so seed longevity for *Agrostemma githago* is implicitly assumed to only extend to the next growing season. Along these lines it

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had been known that the major difficulty in controlling *A. githago* in spring wheat had to do with inadequacies in seed cleaning techniques which resulted in the sowing of the weed seeds in with the crop.

What is most significant about their work was the identification of quantitative thresholds for seed cleaning techniques to be effective in mitigating the increase of weed populations. More than 50% of seeds needed to be removed annually to slow the increase of *A. githago*, and a 90% removal rate was needed for eventual weed eradication. Such information is useful for more than just seed cleaning techniques, but can provide a threshold for determining a necessary level of what Gressel and Segel (1982) refer to as 'effective control'. They point out quite correctly that when weeds that survive an herbicide treatment produce an inordinately large amount of seed, then weed control is compromised, and thus such 'effective control' must be measured in terms of seed production. Firbank and Watkinson provide in the case of one combination of weed and crop a threshold for Gressel and Segel's effective control which results in eradication.

In addition, it was found that in the absence of control a period of six years was sufficient for *A. githago* to go from being of only a negligible density (1 plant/ha) to significantly reducing crop yields.

Lastly, sensitivity analyses using Monte Carlo techniques were invoked in an effort to identify the biological elements most critical to effective control. Parameters describing relationships between mature plant densities and crop yields as well as parameters describing

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survival rates were found to be of greater importance than parameters describing matters of plant competition. In particular minor departures from the 90% control rate threshold were found to result in the effectiveness of the control falling off very rapidly.

Anderson et. al. (1999) created a similar model within the Jointed Goatgrass Initiative (see TABLE 2.7). The model is available at http://www.homepage.montana.edu/~jgg/index.html, along with multiple datasets of empirical values for the constants. The model is intended to serve as a warning indicator for the speed at which jointed goatgrass can quickly thrive in agronomic conditions associated with winter wheat production in the Central Great Plains.

Bussan and Boerboom (2001a) utilized a model identical to the one by the same authors discussed previously to determine that the use of mechanical treatments with herbicide rates at ½ X produced results similar to those of 1X herbicide treatments alone when controlling giant foxtail (*Setaria faberi* Herrm.) in rotations of corn and soybeans. In addition, it was also found that ANR was maximized when herbicides were applied between 3/8 and 9/16 X rates.

2.7 Biological Elements of Special Consideration in Weed Dynamics

With the above comparisons in mind, one is let to examine precisely what processes are of necessary consideration in any effective simulation of weed dynamics. As was

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indicated in the previous paragraph, this is at times highly dependent on the availability of data. However, in the absence of this issue it is of relevance to examine the fullness of what must be understood for a consummate description of why weeds have been so successful and what is necessary for their control.

A set of characteristics often distinguishing weeds from other plants has been defined and, like the plants they describe, widely dispersed. They are:

1. Opportunistic germination
2. Rapid growth and establishment
3. Superior competitive ability
4. Superior environmental tolerance
5. Ability to reproduce without cross-pollination
6. Abundant seed production
7. Continuous seed production
8. Enhanced seed dispersal
9. Seed dormancy

The first element describes the ability of some weeds to germinate opportunistically. A good example of this would be redroot pigweed (*Amaranthus retroflexus*) which is capable of germinating under a wide variety of conditions. Thus in agronomic settings multiple weed control events are usually necessary for the control of such species, making their control more expensive and time-consuming. In the context of the study of invasive species, such

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opportunistic germination often takes the form of early germination, which gives the weed a competitive advantage over later-germinating species. Good examples of this would be spotted knapweed (*Centaurea maculosa*) and leafy spurge (*Euphorbia esula*).

The next three elements are observed in a number of species. Rapid growth and establishment is most fully characterized by an ability to reproduce very soon after germination. Most plants require approximately two months to generate viable seed after flowering. Canada thistle (*Cirsium arvense*) is capable to doing so within two weeks after flowering, and leafy spurge perennates within ten days of germination. Superior competitive ability indicates additional efficiency at environmental resource extraction, and superior environmental tolerance indicates not only a tolerance to conditions in which resources are scarce, but also a tolerance to disturbances as well as an ability to generate a rapid response when resources suddenly become enriched or restored.

The modeling response to the first four elements basically focuses on two categories – emergence and competition. Previous modeling efforts have focused on everything from empirical curves to mechanistic environmental studies. These will be discussed in the upcoming section entitled 'Emergence and Competition'.

Element number five most readily appears in the form of vegetative reproduction in perennial species, which is described in Radosevich et. al. (1997) as taking the form of a variety of reproductive biological mechanisms, including stolons and runners (e.g., *Digitaria sanguinalis*), rhizomes (e.g., *Sorghum halepense*), tubers (e.g., *Helianthus tuberosis*), bulbs

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(e.g., *Allium vineale*), corms (e.g., *Ranunculus bulbosus*), creeping roots (e.g., *Cirsium arvense*, *Convolvulus arvensis*), and stems (e.g., *Taraxacum officinale*). Thus, in such cases the spread of a given weed, especially in agronomic settings, can result from mere fragmentation of existing plants. The appropriate modeling response to this is intuitively unclear, which most likely accounts for its limited modeling history. Some insight, however, may be gained by similar studies involving vertical seed movement from tillage mechanisms, which will be discussed in the section entitled 'Vertical Seed Distribution'.

Abundant seed production is exemplified by numerous weed species. *Linaria dalmatica* can produce up to 400,000 seeds per plant, and *Chenopodium album* can produce up to 500,000 seeds per plant (Beck et al., 2001). In addition, the fact that this seed production is continuous implies an indeterminate and opportunistic flowering. The modeling response to this is straightforward, but it brings to mind several challenging elements of modeling seed rain – namely, its high variability and effects of environmental changes and herbicide application on seed production and viability. Like so many other elements in weed science, the modeling techniques are present, but the data is lacking.

Elements of spatial seed dispersal are extremely complex and arise from a variety of sources. Some sources are biological, dealing with a variety of phenological adaptations that allow for seed rain to fall to the ground at a distance far away from the parent plant (e.g., barbs, hooks, coatings, palatable fruits, wings, plumes, etc.) which enable the seed to make use of not only natural means of dispersal (wind, water, and interactions with animals) as well as artificial means of dispersal (adherence to clothes and vehicles and harvesting with

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crops). Although it may be impossible to capture all possible means of such dispersal, some studies have effectively attempted to capture some of the above elements. These are discussed in the next chapter.

Lastly is the element of seed dormancy. Often described as the means of seed dispersal in time rather than space, this element of weed behavior has been found to be in some species significant to the point of astounding. Seeds of *Convolvulus arvensis* have been observed as retaining their viability even after 50 years of burial (Stubbendieck et. al., 1995). The same has been observed in *Polygonum aviculare* after 400 years, and in *Chenopodium album* after 1700 years (Beck et al., 2001)! As in the case of excessive seed production, this fact of weed phenology is astounding, but the modeling response to this is relatively straightforward.

2.8 Matrix Methods

Inasmuch as a crop rotation is a controlled environment, then it can be treated as a structured periodic system. In a recent work by Mertens et. al. (2002) a periodic matrix model is used to predict the dynamics of two levels in the seed bank of *Polygonum persicaria* under various crop rotation scenarios involving carrots and spring wheat. In particular it is found that the sequence of crops in the crop rotation can play an important role in long-term weed population dynamics.

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The article followed a technique and notation also discussed in Caswell (2001) and Caswell and Trevisan (1994) in which cyclical environmental processes are represented by a periodic matrix models using the following notation. If the environmental cycle involves m time periods and/or processes, then the set of population growth matrices is shown as follows:

$$\mathbf{B}^{(1)},\mathbf{B}^{(2)},\ldots,\mathbf{B}^{(m)}$$

If the population matrix is displayed as follows:

$$\mathbf{n}(t)$$

then population growth over all cycles would be represented as:

$$\mathbf{n}(t+m)=\mathbf{B}^{(m)}\mathbf{B}^{(m-1)}\cdots\mathbf{B}^{(1)}\mathbf{n}(t)=\mathbf{A}^{(1)}\mathbf{n}(t)$$

where the superscript on $\mathbf{A}$ indicates the starting phase. It has been shown that all matrices $\mathbf{A}^{(h)}$ yield the same rate of increase. It is also indicated that a stochastic approach can be used with this method in which matrices are drawn at random from a set of possibilities.

The long-term growth rate of the population over the period of the cycle is given by the largest eigenvalue, $\lambda^{(h)}$, of the matrix $\mathbf{A}^{(h)}$, and since the eigenvalues of all $\mathbf{A}^{(h)}$'s are identical, the superscript will be removed from λ. (This is not to say that all of the $\mathbf{A}^{(h)}$'s are

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themselves identical – indeed, they may be quite different. Only their eigenvalues are identical.) In addition, the associated eigenvector gives an indication of a stable depth distribution of seed concentrations approached over time. In addition, the left eigenvector provides an indication of the 'reproductive values', or the relative contribution of seeds in a given layer to future population growth.

The sensitivity matrix for A is defined as follows:

$$\mathbf{S}_A^{(h)} = \left[\frac{\partial \lambda}{\partial a_{ij}} \right]$$

where

$$\frac{\partial \lambda}{\partial a_{ij}} = \frac{v_i w_j}{\mathbf{w} \cdot \mathbf{v}}$$

where **w** and **v** are the right and left eigenvectors of **A** corresponding to λ. Since the intricacies of matrix multiplication dictate that the entries of **A** are a complex mixture of the entries in each of the $\mathbf{B}^{(h)}$ matrices, the partial derivative indicated above is difficult to interpret. The following sensitivity matrix, however, has an interpretation which is much more straightforward:

$$\mathbf{S}_B^{(h)} = \left[\frac{\partial \lambda}{\partial b_{ij}^{(h)}} \right]$$

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This matrix is calculated via the following:

$$\mathbf{S}_B^{(h)} = \left[\mathbf{B}^{(h)}\mathbf{B}^{(h-1)}\cdots\mathbf{B}^{(1)}\mathbf{B}^{(m)}\mathbf{B}^{(m-1)}\cdots\mathbf{B}^{(h+1)}\right]^{\mathrm{T}}\mathbf{S}_A^{(h)}$$

Similarly, elasticities are defined thus:

$$e_{ij} = \frac{b_{ij}}{\lambda}\frac{\partial\lambda}{\partial b_{ij}}$$

For any single matrix the elasticities of λ with respect to changes in the entries of the matrix sum to 1 and measure the proportional contribution of the matrix entries to population growth.

Increased yields for crops when grown as a part of a crop rotation have been attributed to the periodic environmental changes that prevent the domination of various weeds, diseases, and other pests, as well as reduced stress on the soil due to the inclusion of reduced till crops as well as crops which enhance various soil nutrient inputs. The purpose of this study was a systematic investigation into the effects of different crop rotations on weed populations over the long-term. The three aspects of crop rotations that were investigated were:

1. Effects of a preponderance of a particular crop in the rotation

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2. Effects of the order of crops in the rotation

3. Effects of the number of repeated crops in the rotation

Such an investigation would be prohibitively expensive in an experimental context, but in a simulation context is far more feasible. Previous modeling studies on crop rotations include (Gonzalez-Andujar and Fernandez-Quintanilla, 1991), (Jordan et. al., 1995), and (Lindquist et. al., 1995b).

In this study, the two state variables represent seed bank values at two different levels in the soil:

$$\mathbf{n}(t) = \begin{pmatrix} n_1(t) \\ n_2(t) \end{pmatrix}$$

where here they are represented as a vector. This would be appropriate for a weed seed bank for which it is known that emergence or mortality is a function of depth in the soil. This is appropriate for *P. persicaria*, since it has been found that seeds for this weed do not emerge from depths greater than 5 cm. Thus, this 5 cm depth defines the boundary between the two state variables. What follows is performed according to the notation set in Caswell and Trevisan (1994) and Caswell (2001). Two crops are considered, carrot (crop A) and spring wheat (crop B), and it is assumed that the transition rules only depend on the crop in the present year and not, for example, the crop grown last year. The transition matrices for carrot and spring wheat are, respectively:

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$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$$

where the population after the completion of an AB cycle is:

$$\mathbf{n}(t+2) = \mathbf{B}^{(2)}\mathbf{A}^{(1)}\mathbf{n}(t)$$

where the superscripts indicate the phase of each crop within the rotation. The general equation for the dynamics of a full rotation is as follows:

$$\mathbf{n}(t+p) = \mathbf{M}^{(h)}\mathbf{n}(t)$$

where p is the length of the rotation, and the superscript $h \in \{1 \ldots p\}$ allows for the start time t to be at any position in the rotation. For example, if the reference rotation is AABB, then:

$$\mathbf{M}^{(1)} = \mathbf{B}^{(4)}\mathbf{B}^{(3)}\mathbf{A}^{(2)}\mathbf{A}^{(1)} \qquad \mathbf{M}^{(4)} = \mathbf{B}^{(3)}\mathbf{A}^{(2)}\mathbf{A}^{(1)}\mathbf{B}^{(4)}$$

Using this methodology, different cropping sequences ranging from monocultures to six year rotations were compared for their effects on the growth rate, which incidentally had to be normalized thus for effective comparison:

$$\hat{\lambda} = \sqrt[p]{\lambda}$$

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where p is the length of the rotation, and λ is the dominant eigenvalue of $\mathbf{M}^{(h)}$. In addition, the stable depth distribution and reproductive value distributions approached over the long term are represented respectively by the right ($\mathbf{w}^{(h)}$) and left ($\mathbf{v}^{(h)}$) eigenvectors of $\mathbf{M}^{(h)}$:

$$\mathbf{M}^{(h)}\mathbf{w}^{(h)} = \lambda\mathbf{w}^{(h)} \qquad \mathbf{v}^{(h)^{\mathrm{T}}}\mathbf{M}^{(h)} = \lambda\mathbf{v}^{(h)}$$

The transition matrices were constructed from the following biological processes:

In layer 1, a proportion α_1 of the seeds emerge into seedlings of which a proportion v survives into plants from which γ new seeds per plant are produced. Of the proportion (1 – α_1) that do not emerge, a proportion μ_1 of them experience mortality. In layer 2, a proportion α_2 of the seeds emerge into seedlings which undergo the same processes as seedlings from layer 1. A proportion μ_2 of the seeds which do not emerge undergo mortality.

In addition, the parameters δ_{ij} indicate the proportions of seeds in layer j that move to layer i via tillage events. Lastly, the parameters σ_1 and σ_2 govern the overwintering survival rates for seeds in the two layers.

Thus, the four elements in each transition matrix can be constructed thus:

$$a_{11} = \alpha_1 v\gamma\delta_{11}\sigma_1 + (1-\mu_1)(1-\alpha_1)\delta_{11}\sigma_1$$

$$a_{12} = \alpha_2 v\gamma\delta_{11}\sigma_1 + (1-\mu_2)(1-\alpha_2)\delta_{12}\sigma_1$$

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$$a_{21} = \alpha_1 v\gamma\delta_{21}\sigma_2 + (1-\mu_1)(1-\alpha_1)\delta_{21}\sigma_2$$

$$a_{22} = \alpha_2 v\gamma\delta_{21}\sigma_2 + (1-\mu_2)(1-\alpha_2)\delta_{22}\sigma_2$$

In particular there is great uncertainty in the overwinter survival parameters, and in the case of the tillage seed movement parameters there is the potential for great variability. Thus, sensitivity analyses were performed on these parameters.

The following findings were documented:

1. In general an increase in the preponderance of crop A (carrot) in the rotation was associated with lower values of $\hat{\lambda}$.

2. In the baseline scenario, where overwinter survival rates were set at 100%, rotation patterns in which crops ran consecutively had lower $\hat{\lambda}$ rates than those which had alternating crops. In other scenarios in which the survival rates were lowered to 80% and 50%, the reverse effect occurred.

3. Sensitivity analyses indicated that tillage played a large role in the population dynamics by cyclically moving the seeds into alternating soil layers from year to year. When tillage is removed, rotations that differ only in the crop sequence had very similar results, presumably because the removal of tillage effectively decoupled the dynamics of the two soil layers.

4. Sequence, in addition to a variety of environments, appears to now play a vital role in the impacts on weed populations in crop rotations.

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It was also stated that the methods described here could be extended to include density dependence, effects of environmental variation on vital rates, and increasing the number of modeled soil layers.

2.9 Summary

It appears that ecological modeling, though merely a tool with its own set of limitations, is a technique whose usage in agronomic weed management should be on the rise in the future, due to changes in the sociopolitical climate that recognize its utility as well as a strong diversity of model types and potential uses that allow for a variety of applications. These potential applications include the creation of decision-making tools for the determination of thresholds for herbicide application, optimal products, and optimal herbicide rates and times of application. As studies become more plentiful, the prospect of presenting decision-making options in the context of a format of risk-assessment becomes more feasible. The use of dynamic simulation models allows for the prospect of evaluating different options with respect to a long-term focus that can involve inter-seasonal rotations of crops and herbicides.

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Parameter	Description	Value
C_c	Price of Corn	\$2.20 / bu
Y_{wf}	Weed-free yield	176 bu/acre
C_a	Cost of Application	\$2.00 / acre
I	Proportional yield loss by first unit increase of weed density	0.015
A	Maximum proportional yield loss	0.5
$\varepsilon_{H,\max}$	Maximum herbicide efficacy at high herbicide rates	1
k	Rate of exponential increase of efficacy with rate	4

TABLE 2.1, Bioeconomic parameters for glyphosate control of giant foxtail (exponential dependence of herbicide efficacy on herbicide rate).

Parameter	Description	Value
$\varepsilon_{H,\max}$	Maximum herbicide efficacy at high herbicide rates	1
H_{50}	Rate at which efficacy approaches half the maximum rate	0.7
b	Rate of efficacy increase with herbicide rate	1

TABLE 2.2, Bioeconomic parameters for glyphosate control of giant foxtail (logistic dependence of herbicide efficacy on herbicide rate).

Bauer and Mortensen (1992) – Velvetleaf and Sunflower in Soybeans		
Purpose and Focus: The determination of optimal long-term EOT as a function of herbicide application thresholds where in particular seed banks are simulated with explicit reference to seed age.		
Seedlings	$G_t = (1-\varepsilon_T)\sum_{i=1}^{n} S_{t,i}\frac{a_w}{i+b_w}$	Hyperbolic with seed age, constant tillage efficacy
Mature Plants	$N_t = (1-\varepsilon_H)G_t$	Constant herbicide efficacy
Seed Rain	$R_t = (1-\mu_o)\phi N_t$	Constant fecundity and overwintering mortality
Seed Bank	$S_{t+1,1} = R_t$ $S_{t+1,i+1} = (1-\mu_s)S_{t,i}$	Constant annual seed bank mortality, explicit modeling of seed age
Yield Loss	$y_{L,n,t} = IN_t$	Constant linear function with weed density

TABLE 2.3, Algorithmic summary of Bauer and Mortensen (1992).

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Gonzalez-Andujar and Fernandez-Quintanilla (1991) - *Avena sterilis* in corn		
Purpose and focus: The determination of weed dynamics in response to variations in herbicide efficacy, the use of tillage, rotation modification, and cohort-specific timing.		
Seedlings	$G_{t,j} = \alpha_j S_{t,j}$	Constant emergence for two plant cohorts
Mature Plants	$N_{t,j} = \frac{(1-\varepsilon_j)G_{t,j}}{1+a_j G_{t,j}}$	Cohort specific – modeled with density dependence and constant control efficacy
Seed Rain	$R_t = \sum_{j=1}^{2} \frac{(1-\mu_o)\phi_j N_{t,j}}{1+b_j N_{t,j}}$	Cohort specific – modeled with density dependence and constant overwintering mortality
Seed Bank Survival	$S_{t+1} = S_t \prod_{k=1}^{3}(1-\mu_{s,k}) \prod_{j=1}^{2}(1-\alpha_j) + R_t$	Explicit season depiction, each with constant seed bank mortality

TABLE 2.4, Algorithmic summary of Gonzalez-Andujar and Fernandez-Quintanilla (1991).

Bussan and Boerboom (2001b) – Velvetleaf in corn and soybeans		
Purpose and focus: Determination of yield loss in response to explicit modeling of variable herbicide rates, optional tillage, and a bio-control agent		
Seedlings	$G_t = \alpha S_t$	Constant emergence
Mature Plants	$N_t = (1-\mu_g)(1-\delta\varepsilon_{T,r})(1-\varepsilon_H)G_t$	Optional constant tillage mortality, variable herbicide mortality from herbicide rate
Seed Rain	$R_t = \phi N_t e^{-\beta N_t}$	Density-dependence with herbicide rate influence
Seed Bank Survival	$S_{t+1} = (1-\mu_s)(1-\alpha)S_t + (1-\mu_o)R_t$	Constant seed bank and overwintering mortalities
Biomass	$B_t = \tilde{\beta}_1 N_{m,t} e^{-\tilde{\beta}_2 N_{m,t}}$	Density-dependence with herbicide rate influence
Yield Loss	$Y_{L,t} = \eta B_t$	Constant linear relationship to biomass

TABLE 2.5, Algorithmic summary of Bussan and Boerboom (2001b).

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Firbank and Watkinson (1986) – *Agrostemma githago* L. in spring wheat		
Purpose and focus: Determination of speed in which in the absence of control weed populations become yield reducing; determination of necessary control degree for effective management.		
Seedlings	$G_{w,t} = \alpha_w S_{w,t}$ $G_{c,t} = \alpha_c S_{c,t}$	Constant emergence
Mature Plants	$N_{w,t} = \frac{G_{w,t}}{1+\beta_w\left(G_{w,t}+\gamma_{wc}G_{c,t}\right)}$ $N_{c,t} = \frac{G_{c,t}}{1+\beta_c\left(G_{c,t}+\gamma_{cw}G_{w,t}\right)}$	Hyperbolic density-dependence which includes densities of both species
Biomass	$B_{w,t} = \frac{B_{w,\max}}{\left[1+\beta_w\left(N_{w,t}+\delta_{wc}N_{c,t}\right)\right]^{b_w}}$ $B_{c,t} = \frac{B_{c,\max}}{\left[1+\beta_c\left(N_{c,t}+\delta_{cw}N_{w,t}\right)\right]^{b_c}}$	Sigmoidal density-dependence which includes densities of both species
Seed Production	$R_{w,t} = \phi_w B_{w,t}^{k_w} N_{w,t}$ $R_{c,t} = \phi_c B_{c,t}^{k_c} N_{c,t}$	Seed Production per plant as a function of biomass
Seed Bank	$S_{w,t+1} = (1-\varepsilon)\frac{R_{w,t}}{R_{c,t}} S_{w,t}$	Sowing of weed seeds as a function of the proportion of total seeds made by weed plants, combined with a control efficacy

TABLE 2.6, Algorithmic summary of Firbank and Watkinson (1986).

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Anderson et. al. (1999) – Jointed goatgrass (*Aegilops cylindrica*) in winter wheat		
Purpose and focus: Prediction of long-term bioeconomic effects of increased jointed goatgrass densities in agronomic settings		
Seedlings (spring)	$G_{w,t} = \left[(1-\mu_{12})\alpha_{w,1} + \alpha_{w,2}\right]S_{w,t}$	Constant emergence with two cohorts
	$G_{c,t} = \alpha_c S_{c,t}$	Constant emergence with seeding rate
Reproductive Tillers	$T_{w,t} = \frac{T_{w,\max} G_{w,t}}{d + G_{w,t}}$	Hyperbolic density-dependence
	$T_{c,t} = (1-\mu_g)G_{c,t}$	Constant seedling survival parameter
Seed Production	$R_{w,t} = \frac{2\phi T_{w,t}}{1+\beta(T_{w,t} + \gamma T_{c,t})}$	Hyperbolic two-species density-dependence
Crop Yield	$Y = Y_{\max}\left(1 - \frac{iT_{w,t}}{1 + iT_{w,t}/A}\right)$	**(Option 1)** Hyperbolic dependence on weed density
	$Y = \frac{jT_{c,t}}{1 + jT_{c,t}/Y_{\max}}\left(1 - \frac{iT_{w,t}}{1 + iT_{w,t}/A}\right)$	**(Option 2)** Hyperbolic two-species density dependence
Seed Bank	$S_{w,t+1} = (1-\varepsilon_r)R_{w,t} + (1-\mu_s)(1-\alpha_{w,1}-\alpha_{w,2})S_{w,t}$	Annual seed bank mortality combined with annual seed production with a removal efficacy

TABLE 2.7, Algorithmic summary of Anderson et al. (1999).

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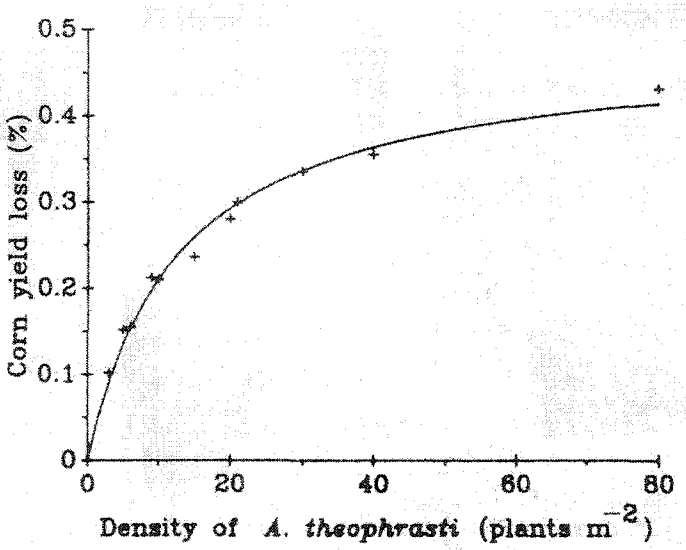

FIGURE 2.1, from Sattin et al. (1992), showing a hyperbolic relationship between corn yield loss and density of velvetleaf (*Abutilon theophrasti*).

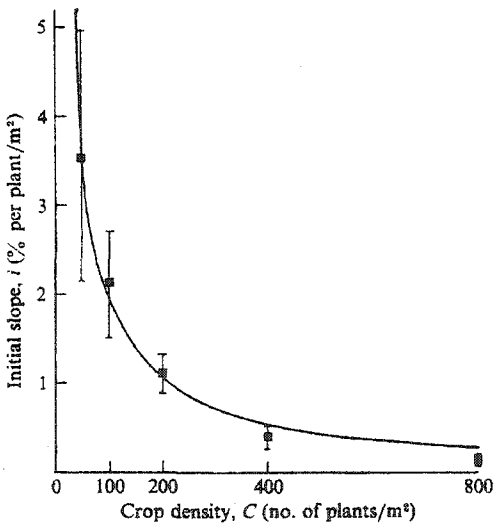

FIGURE 2.2, from Cousens (1985b). Analysis performed on data from Hakansson (1983) showing variation of the *s* parameter as a function of crop density.

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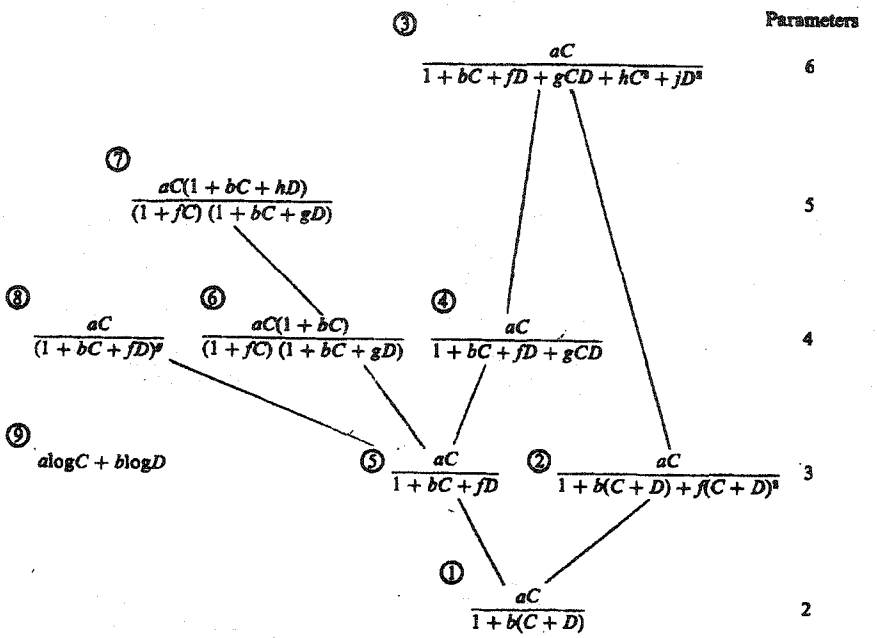

FIGURE 2.3, from Cousens (1985b) illustrating Cousens' methodology of grouping competing models by formulation and number of parameters.

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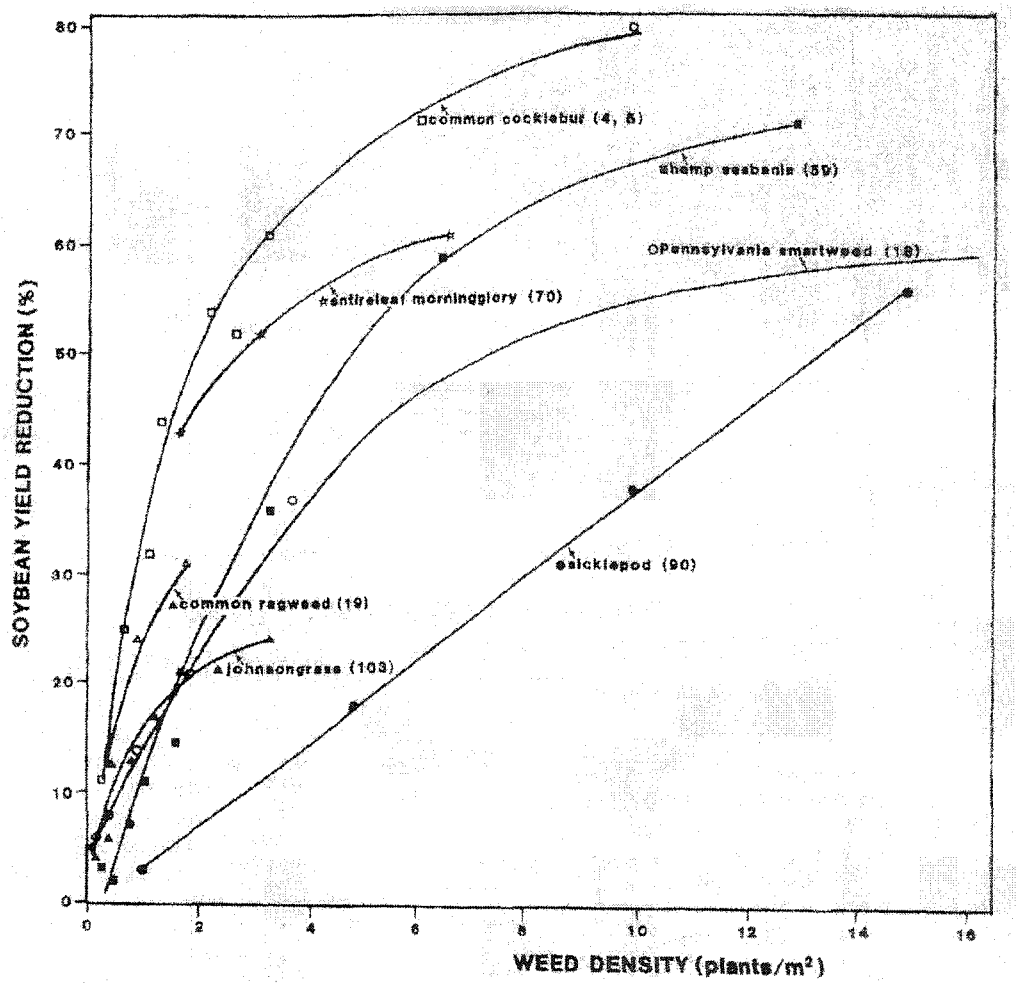

FIGURE 2.4, from Stoller et al. (1987), showing hyperbolic relationships between densities of various weed species and soybean yield loss.

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Equation[a]	Crop[b]	Weed[b]	Reference
1. $y = aC/(1 + b(C + N))$	barley	white mustard	33
2. $y = aC/(1 + b(C + N) + f(C + N)^2)$	barley	white mustard	33
3. $y = aC/(1 + bC + fN + gCN + hC^2 + jN^2)$	barley	white mustard	33
4. $y = aC/(1 + bC + fN + gCN)$	corn	peanut*	73
5. $y = aC/(1 + bC + fN)$	corn	peanut*	73
6. $y = aC/((1 + bC + fN)(1 + g(1 + bC + fN)))$	corn	peanut*	74
7. $y = aC(1 + bC)/((1 + fC)(1 + bC + gN))$	barley	white mustard	13
8. $y = aC(1 + bC + hN)/((1 + fC)(1 + bC + gN))$	barley	white mustard	13
9. $y = aC/(1 + bC + fN)$#	wheat	corn cockle	80
10. $y = a\log C + b\log N$	corn	peanut*	73
11. $y = ae^{-bN}(1 - e^{-fC})$	wheat	cheat	9
12. $y_L = aN/(C + aN)$	wheat	annual ryegrass	48
13. $y_L = aN/(bC + (1 + b)N)$	wheat	wild oats	7
14. $y_L = ((a - 1)C + bN)/(aC + bN)$	wheat	annual ryegrass	46
15. $y_L = ((a - 1)C + (b - 1)N)/(aC + bN)$	wheat	annual ryegrass	46
16. $y_L = a + b\log N - b\log C$	wheat	annual ryegrass	46
17. $y_L = a + b\log N - b\log(C + N)$	wheat	annual ryegrass	46
18. $y_L = a + b\sqrt{N/C}$	wheat	annual ryegrass	46
19. $y_L = a\sqrt{N/(C + N)}$	wheat	wild oats	7
20. $y_L = a + b\sqrt{N/(C + N)}$	wheat	annual ryegrass	46
21. $y_L = 1 - a(C/N)^b$	wheat	annual ryegrass	46
22. $y_L = 1 - a((C + N)/N)^b$	wheat	annual ryegrass	46
23. $y_L = aN/(C + N) + bN^2/(C + N)^2$	wheat	wild oats	7

[a]C is crop density N is weed density, a, b, f, g, h, j are arbitrary parameters. The yield loss equation is given where no yield equation was specified; * denotes inter-cropping study. Many of the equations were compared statistically in the original papers and some found more suitable than others.

[b]Crop and weed species referred to here for the first time and not mentioned elsewhere in the text: white mustard (*Sinapis alba* L. # SINAL) and peanut (*Arachis hypogaea* L.)

FIGURE 2.5, from Cousens et al. (1987b), showing the wide variety of empirical functions utilized for the quantitative depiction of the effect of weeds on yield loss in cereal crops.

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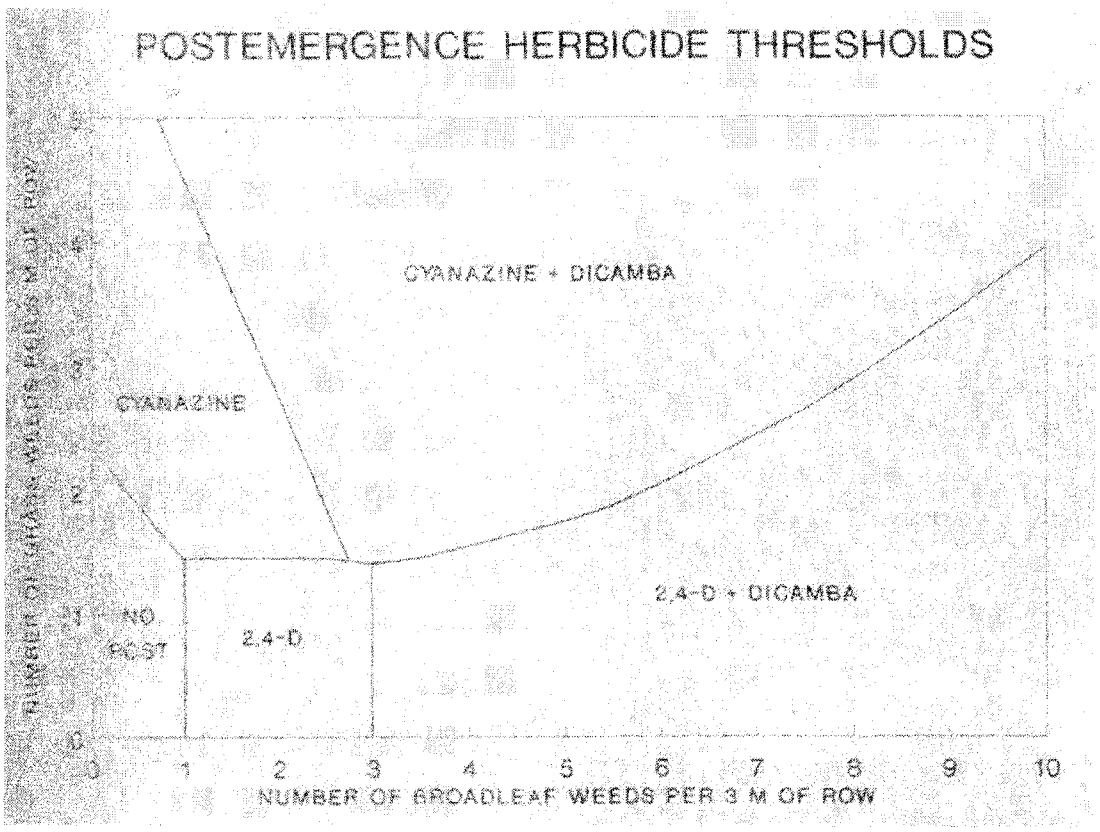

FIGURE 2.6, from Lybecker et al. (1991), showing regions of weed population scenarios for which different products are deemed optimal for control.

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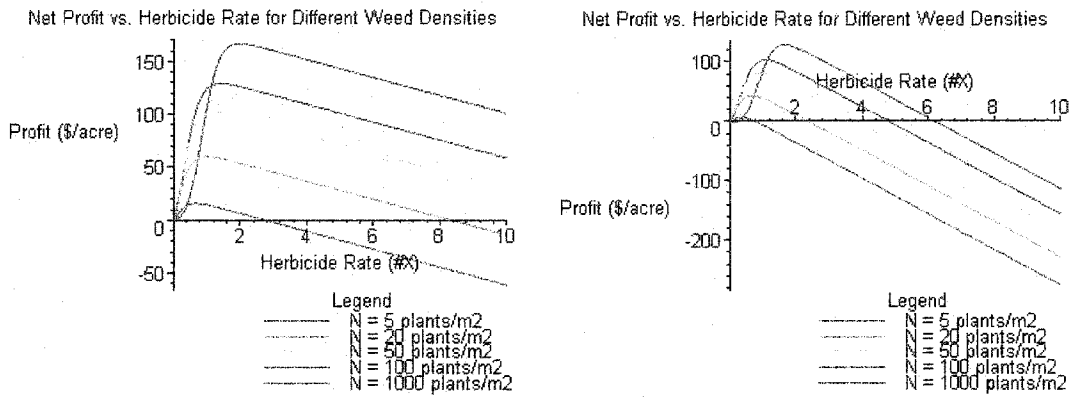

FIGURE 2.7a, showing net profits plotted as herbicide rate increases, where different lines show different initial weed densities, and the two graphs display results for two different herbicide prices (C_h = \$8.50 / acre and \$30.00 / acre, respectfully.)

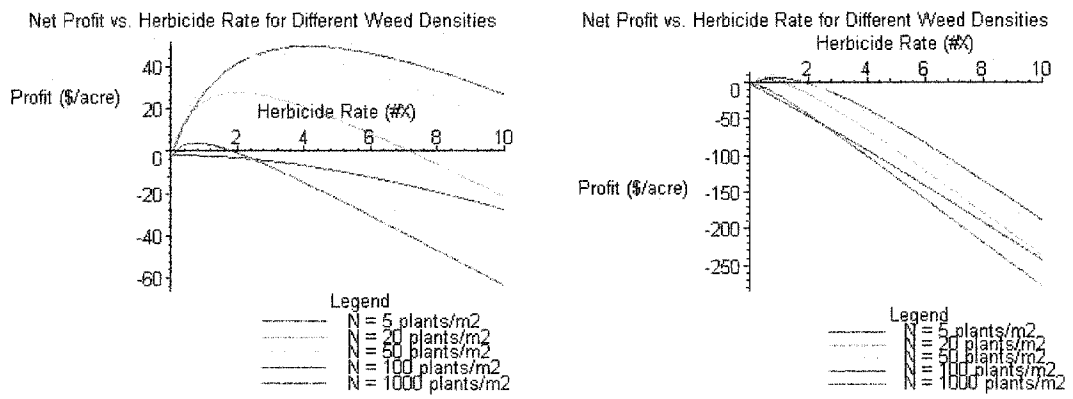

FIGURE 2.7b, same as FIGURE 2.7a except that a logistic relationship between herbicide rate and herbicide efficacy is utilized.

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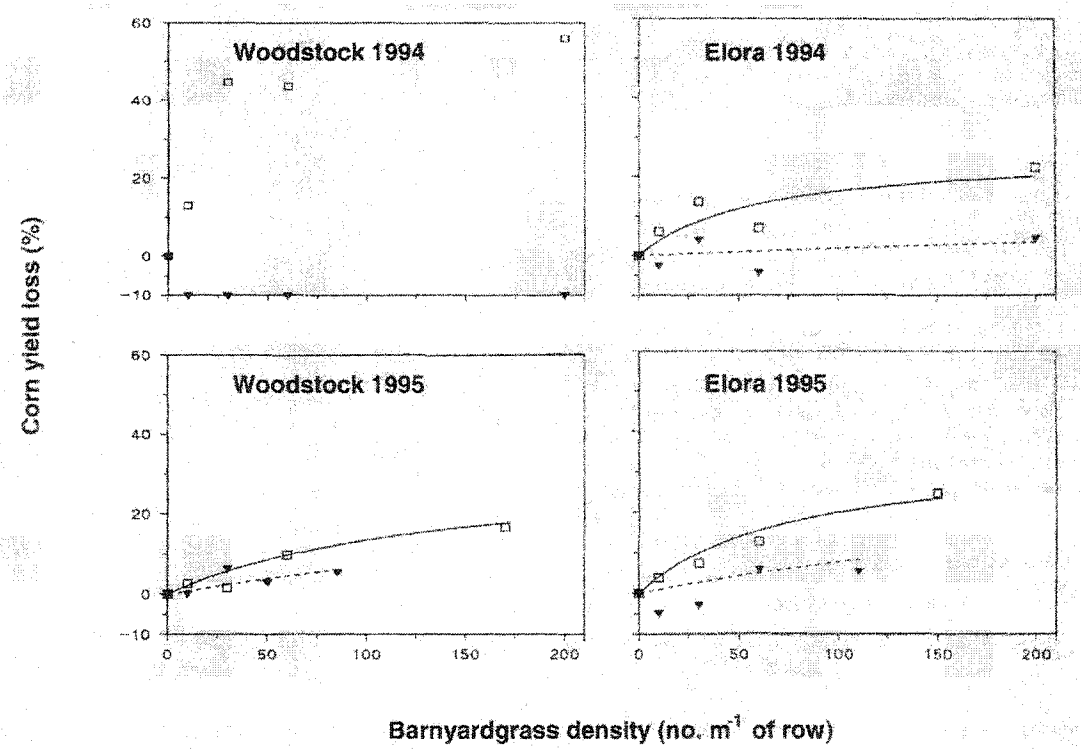

FIGURE 2.8, from Bosnic and Swanton (1997a), showing hyperbolic relationships between densities of barnyardgrass (*Echinochloa crus-galli*) and yield loss in corn (*Zea mays*). Results are displayed for two years at two sites.

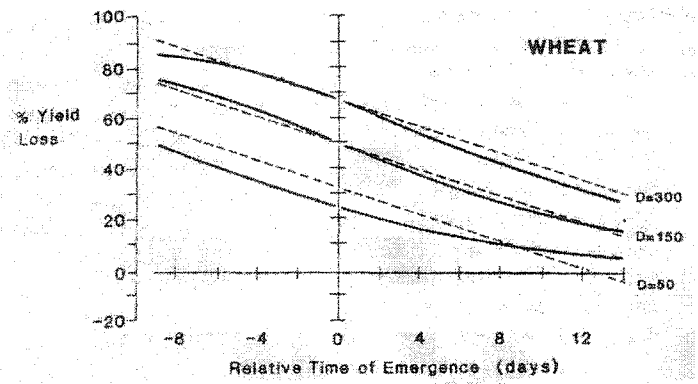

FIGURE 2.9, from Cousens et al. (1987a), showing relationships between relative time of emergence of wild oat in a wheat crop and wheat yield loss, shown for three densities of wild oat.

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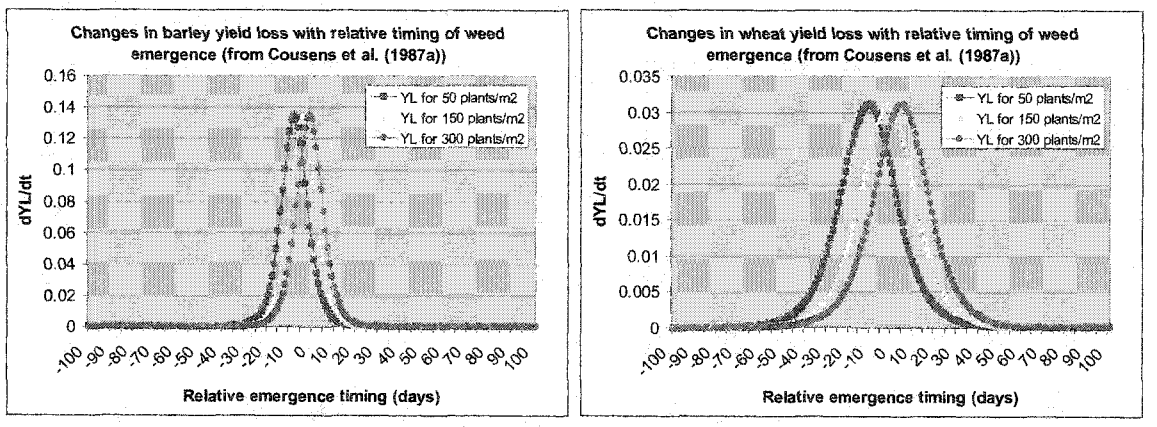

FIGURE 2.10, showing a analysis of data from Cousens et al. (1987a), showing changes in yield loss with relative time of emergence ($t_w - t_c$) for three weed densities in barley and wheat.

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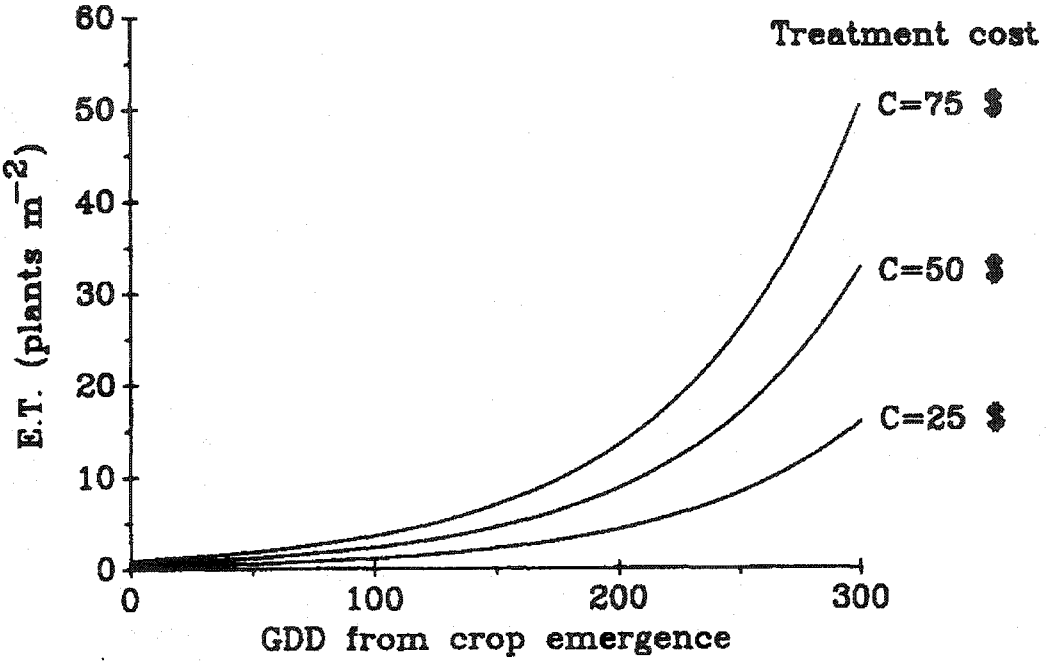

FIGURE 2.11, from Sattin et al. (1992), showing variation of economic thresholds (ET) of velvetleaf with emergence timing and treatment cost.

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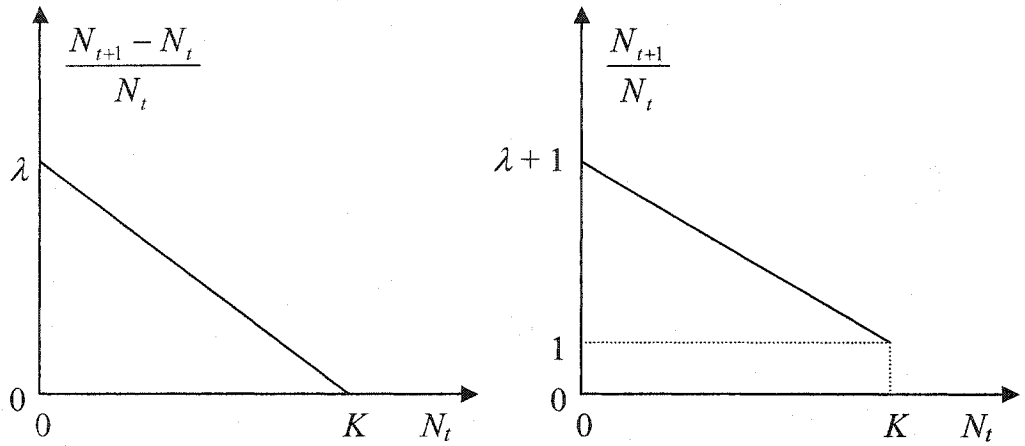

FIGURE 2.12, showing in two graphical forms the quantitative assumptions made in the derivation of the standard logistic equation.

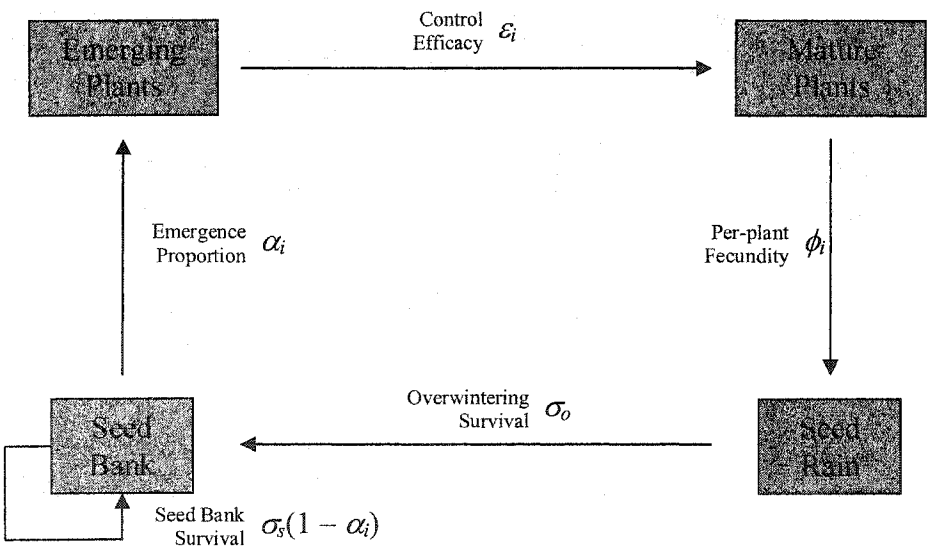

FIGURE 2.13, Diagram showing the essential demographic processes of an annual weed species.

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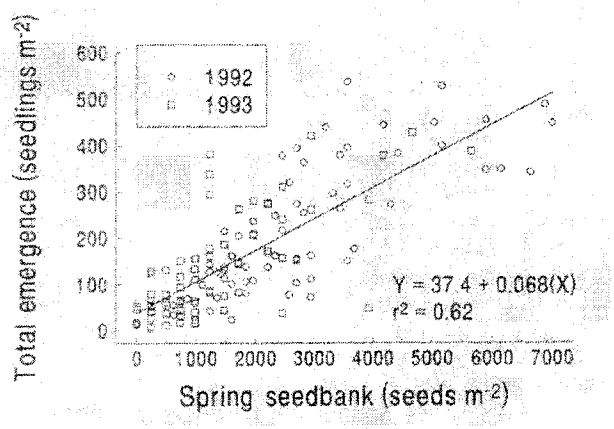

FIGURE 2.14, from Lindquist et al. (1995a), showing total cumulative emergence as a

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Chapter 3.0
Literature Review II: Advanced Elements

"A weed is no more than a flower in disguise."
James Russell Lowell

Modeling in weed science is to a large extent in a process of transition, one which is reflective of the fact that it is experiencing an influx of people and techniques from outside disciplines. As was stated in the previous chapter, much of this new information involves principles of plant interference from ecology, more complex analysis techniques from statistics, and more sophisticated processes of simulation from mathematics and computer science. In this chapter previous work on this more innovative level is described, and as before some new ideas from the present author are also included.

3.1 Plant Interference on the Level of the Individual

To continue the discussion of the effects of weed density on yield loss, as well as to introduce a first example of a more mechanistic modeling approach, the following introductory mathematical investigation of plant competition is presented:

Inasmuch as resource usage, and, thus, yield loss per plant $\frac{Y_L}{N_c}$ can be represented as a circle of ground containing resources that the plant utilizes (shown in FIGURE 3.1

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with area A and radius r), then plant competition can be represented by the extent to which a given plant's circle of influence is invaded by other plants, and vice-versa. A derivation of an analytical relationship describing this reduction in the plant's resource utilization, and, thus, its competitive influence can be instrumental in developing a full theoretical framework for assessing true density dependence of the influence weeds have on crops. It can also serve to create a theoretical forum in which the effects of patchiness and spatial heterogeneity can be effectively modeled.

For simplicity, we begin with two plants whose circles of influence invade each other. For each plant their loss of available resources can be represented via a chord sent through the circle, bounded at the points at which the two arcs intersect (see FIGURE 3.2). For a plant having a circle of influence of radius r this loss of area, and, thus, available resources would be as follows:

$$A_L = \frac{A\theta}{2\pi} - \frac{bh}{2} = \frac{\theta}{2\pi}(\pi r^2) - \frac{bh}{2} = \frac{\theta}{2} r^2 - \frac{bh}{2} = \frac{r^2}{2}\cos^{-1}\left[\frac{h}{r}\right] - \frac{h}{2} \bullet 2\sqrt{r^2 - h^2}$$

$$\therefore A_L = \frac{r^2}{2}\cos^{-1}\left[\frac{h}{r}\right] - h\sqrt{r^2 - h^2}$$

where b and h represent, respectively, the length of the chord and its distance to the circle's center. A is the circle's total area, and θ is the size of the angle subtended by the arc. Note that the final equation shows the loss of area A_L as a function of r and h only. For two plants having identical r's, h would simply be half the distance between the plants.

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For plants having different values of r (i.e., different species possessing different quantities of resource utilization) as well as instances in which more than two plants are mutually interfering, the investigation would require numeric integration, assumptions concerning degrees of aggregation, and possible multiple runs in a stochastic fashion. This is all very realistic given present computational techniques and capabilities.

To be sure, this treatment is very simplistic, and ignores phenological differences in the vertical profiles of plant canopy and plant soil nutrient utilization, and it provides a measure of plant competition that is only applicable for a single moment, and, thus, would need to be combined with relationships involving relative plant emergence and environmental effects in order to be fully applicable. Still, it provides a good example of a highly mechanistic approach to plant competition, and, considering that existing empirical models of yield loss due to weed densities involve instances in which only a single weed species is present in the crop, such mechanistic approaches may prove to be both vital and fruitful in future studies.

This is especially visible given the following derivation concerning intraspecific competition. Beginning with the hyperbolic relationship from before:

$$Y = Y_{\max} \frac{N}{n_{50} + N}$$

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where in this case 'yield' can mean crop yield or weed seed production. It is kept general, describing intraspecific competition in a form that could also be described as a Michaelis-Menten feedback equation. In this form, yield per plant is:

$$\frac{Y}{N} = Y_{\max} \frac{1}{n_{50} + N}$$

Considering our circular region of influence from before, an area per plant can be defined as:

$$A = \pi\left(\frac{s}{2}\right)^2 = \frac{1}{N}$$

where s is an average distance from one plant to its neighbor. Dividing this distance in half yields a radius for these spherical regions of influence, the area of which is the reciprocal of the plant density. This yields an expression to substitute for N:

$$\frac{Y}{N} = Y_{\max} \frac{1}{n_{50} + \frac{4}{\pi s^2}}$$

or,

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$$\frac{Y}{N} = \frac{Y_{max}}{n_{50}\left(\frac{4}{\pi n_{50}} + s^2\right)} \qquad [3.1]$$

This hyperbolic relationship is plotted in the first graph of FIGURE 3.3, where the unit of distance on the x-axis is $\frac{2}{\sqrt{\pi n_{50}}}$ since this is the square root of the first term in the denominator above. (Note that the first unit of distance results in yield per plant which is half the maximum.) Inverting this relation by subtracting it from one yields the second of the two graphs, which shows a curve that, if rotated around the y-axis, would create a three-dimensional quasi-Gaussian surface illustrating a spatial region of competitive influence of a single plant. Since the original hyperbolic function from which this curve is derived is time-independent, so is this resulting curve, showing a spatial region of influence integrated over the entire growing season.

FIGURE 3.4 from Pike et. al. (1990) shows the above study in experimental form, showing a clear relationship between interspecific plant distances and plant yield. Firbank and Watkinson (1987) performed a similar analysis within monocultures of *Agrostemma*, plotting shoot dry weights of individual plants against the number of plant neighbors within one of four radii. Although trends were somewhat visible and were deemed statistically significant, a great deal of variability was also present. The paper went on to account for some of the variability through differences in relative time of emergence, but only to a limited extent. Even in the context of a highly controlled

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experiment, the cause of a large degree of the experimental variation remained undetermined, which was consistent with the findings of Casper and Jackson (1997) who describe the intricacies of belowground competition as a highly complex set of interactions involving water availability, assimilation of up to 20 different plant nutrients, and interactions with aboveground competition.

Studies by Weiner (1982, 1984) have attempted to further quantify this spatial interference relationship by representing the seed production of a given plant thus:

$$R = \frac{R_{\max}}{1 + W}$$

where $R_{\max}$ is the maximum seed yield per plant, and W is the effect of competition:

$$W = \sum_{i=1}^{n} \frac{1}{d_i^2} \sum_{j=1}^{m} C_j N_{ij}$$

where for a total of n neighborhoods, the distance from the plant to neighborhood i is denoted d_i, and for a total of m species the competitive effect of a given plant of species j is denoted C_j. The number of plants of species j in neighborhood i is denoted N_{ij}. Interference relationships were more clearly visible in these studies, but the situations were more specialized (sparsely populated *Polygonum* species in shallow soil, and *Pinus rigida*) and less applicable to agronomic settings.

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Pacala and Silander (1987) did a study involving interactions among *Abutilon theophrasti* and *Amaranthus retroflexus*. Above-ground biomass for each species i was fit to a similar equation:

$$B_i = \frac{B_{i,\max}}{1 + c_{ii}N_i + c_{ij}N_j}$$

where N_i and N_j are the densities of species i and j, respectively. $B_{\max,i}$ is the maximum biomass of species i, and c_{ii} and c_{ij} respectively provide empirical estimates of intraspecific and interspecific competition. The fact that this equation is hyperbolic implies a proportional relationship between plant biomass and plant yield, which was confirmed in the present study with successful empirical fits to the following equation:

$$Y_i = \beta_0 + \beta_1 B_i$$

where β_0 and β_1 are empirical parameters relating the biomass of species i, B_i, to the yield of the same species, Y_i.

Studies like Spitters, Kropff, and de Groot (1989) have also approached interference modeling from a slightly different angle, doing linear regressions of reciprocal per-plant biomass and reciprocal per-plant yield on crop and/or weed densities:

$$\frac{1}{y} = \mu + \beta_i N_i$$

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where y is the per-plant corn yield, N_i is either crop or weed density, and μ and β_i are regression parameters. The fact that successful linear regressions have been made relating the above quantities by multiple authors gives support to the theoretical notion that a linear relationship exists between reciprocal per-plant biomass or yield and variations in plant density.

From a generalized mathematical notion this linear relationship is expressed thus[2]:

$$\frac{\partial}{\partial N_i}\left(\frac{N_c}{Y}\right) = \beta_i$$

where N_c is the crop density, N_i is the density of weed species i, and β_i is the linear relationship between reciprocal per-plant crop yield and density of weed species i. This is equivalent to the following[2]:

$$\frac{N_0}{Y} = \mu + \sum_{i=0}^{n} \beta_i N_i$$

where a total of n weed species is modeled, and crop density is in this case denoted as N_0. Note that the summation includes the effects of the crop on itself ($i = 0$) as well as the effects of n weed species.

[2] Excluding interactions.

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For studies of intraspecific crop competition, this theory is identical to that of Cousens (1985):

$$\frac{N_0}{Y} = \mu + \beta_0 N_0$$

$$Y = \frac{N_0}{\mu + \beta_0 N_0}$$

$$Y = \left(\frac{1}{\beta_0}\right)\frac{\left(\beta_0 / \mu\right)N_0}{1 + \left(\beta_0 / \mu\right)N_0}$$

where equivalent values of I and A are observed. For interspecific competition, however, a slight difference exists:

$$\frac{N_0}{Y} = \mu + \beta_0 N_0 + \beta_1 N_1$$

$$Y = \frac{N_0}{\mu + \beta_0 N_0 + \beta_1 N_1}$$

related to the fact that this predicts a sigmoidal response to weed density N_1, instead of hyperbolic.

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Inasmuch as the competitive effect of a plant on its surroundings is a strong function of its size, some highly complex plant biometry models have also been developed (e.g., Charles-Edwards, 1982), but only for a very limited set of species. They require a great deal of environmental information on environmental conditions of light, water, and soil nutrients. Most predict various aspects of plant phenology, especially leaf area (e.g., Dunan et al, 1999). This will be described more fully in section 3.5.

To describe this in less mechanistic terms, Mutsaers (1989) proposes a generalized dynamic equation for plant interaction:

$$\frac{d^2 B_i}{dt^2} = \left(\frac{d^2 B_i}{dt^2}\right)_{\max} \left[1 - \frac{1}{A} \sum_{j=1, j \neq i}^{n} \frac{dB_j}{dt}\right] \qquad [3.2]$$

where B_i is the biomass of a single plant i. Thus, the time derivative of this variable is the plant growth rate, and its second derivative is the change in the plant's growth rate. Linguistically, the above equation states that the change in a plant's growth rate at a given time is a fraction the maximum change in plant growth rate (under no competition). This fraction is found by subtracting from one the total of all plant growth rates in a neighborhood of n plants per unit area divided by a maximum possible growth rate of all plants per unit area (A). The variable A is resource-driven. Though purely theoretical, it provides an effective summary of the present conceptual thought surrounding individual plant competition.

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Bussler et al. (1995) effectively combines two of the above concepts into what appears to be a very effective modeling technique. The technique involves representing individual plants as circular cylinders, thus combining the circular horizontal area concepts and biomass together. Clearly the need for further study here is indicated, and this particular technique may represent an important venue within which this should be done.

3.2 Plant Interference on the Level of the Community

In the previous chapter interference effects were examined in the context of a single plant. However, numerous experimental studies have also taken place to quantify plant interactions on the community level. Such studies usually result in measurements of plant yield or biomass per unit area of a given species modeled as a function of the density of that species as well as a competing species. In addition, such studies oftentimes attempt to detect the critical timing of this competitive interference. Both aspects pose significant agronomic implications. Studies from the previous chapter involving crop-weed interactions would be a good example of this, but in this section more general studies from the field of ecology are described.

FIGURE 3.5, from Lodge (2000), shows an example of an experimental tool that is used in providing an assessment of interspecific plant interaction. Such experiments, referred to as 'replacement series' experiments, calculate plant biomass for two species

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grown together in varying degrees of predominating densities. Keeping the total density ($N_w + N_c$) constant, the proportion of each species in the total density is varied. The figure shows an example of a series of such experiments performed on three perennial grasses (*Deanthonia linkii* Kunth cv. Bunderra, D. *richardsonii* Casmore cv. Taranna, and *Phalaris aquatica* L. cv. Sirosa) in combination with three competing species – white clover (*Trifolium repens* L.), subterranean clover (*Trifolium subterraneum* L. var. *brachycalycinum*) and annual ryegrass (*Lolium rigidum* L.). Such experiments provided insight into the best choices for perennial grass introduction. Note that the curves display the same general hyperbolic shape as in the studies shown previously.

It should be noted that replacement studies address the issue of plant competition from a different perspective than studies discussed before. FIGURE 3.6, from Rejmanek et al. (1989), illustrates how these and all other studies have the potential of providing different pieces of the general picture of crop-weed interaction, or, for that matter, interactions between any two species. The figure shows four categories of plant competition study and indicates the portions of the full range of crop and weed densities that are investigated by each study type. Traditional crop-weed interaction studies can be likened to the partial additive studies shown in part A of the figure, where interference analyses are made for a series of weed densities, but for only a single crop density. Intraspecific crop competition studies such as row spacing studies would be similarly classified but with a horizontal row of dots. Replacement series experiments are indicated in part B, where total density is kept constant, but individual species densities are varied. Rejmanek indicates that such studies, while very useful, indicate an implicit

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assumption that the dynamics of plant interference are only dependent on relative species proportions and show no interactions with either total plant density or the densities of either species. The suggestion is made that additive series such as those shown in parts C and D represent the next logical step in gaining a full picture of interference between two plant species.

Competition studies have also focused on densities instead of biomass. In a study by Jacobs, Sheley, and Maxwell (1996) the objectives were to evaluate the efficacy of *Sclerotinia sclerotiorum* as a biocontrol agent, to quantify the competitive interaction between knapweed and wheatgrass at high densities, and to further quantify this interaction under the influence of *Sclerotinia*.

A series of growth chamber studies were performed in which combinations of wheatgrass and knapweed were grown under high seeding densities. Fungal inoculations were performed two weeks after emergence of the knapweed. Analyses involved AOV, regressions, and Fisher's protected LSD comparisons with $\alpha = 0.05$.

One set of regressions was as follows:

$$N_k = \beta_{k,0} + \beta_{kk} n_k + \beta_{kw} n_w \qquad N_{k,s} = \beta_{k,0,s} + \beta_{kk,s} n_k + \beta_{kw,s} n_w$$

where the letters n and N represent seeding and harvest densities, respectively, and the letters k and w represent knapweed and wheatgrass, respectively. The first equation is for

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instances without *Sclerotinia* and the second is for instances with *Sclerotinia*. Similarly, the equations for wheatgrass harvest density are as follows:

$$N_w = \beta_{w,0} + \beta_{ww} n_w + \beta_{wk} n_k \qquad N_{w,s} = \beta_{w,0,s} + \beta_{ww,s} n_w + \beta_{wk,s} n_k$$

Similar regressions were also performed with the reciprocal of the average harvest weight (equivalent to the average number of plants per unit weight) as the dependent variable. The β values are termed 'competition coefficients', and relative competitive abilities between two species can be obtained via ratios of interspecific and intraspecific coefficients:

$$\kappa_{k,wk} = \frac{\beta_{kw}}{\beta_{kk}} \qquad \kappa_{w,kw} = \frac{\beta_{wk}}{\beta_{ww}}$$

where in this case the two ratios describe the relative influence that wheatgrass has over knapweed in determining knapweed harvest numbers, and the relative influence that knapweed has over wheatgrass in determining wheatgrass harvest numbers.

In addition, the following ratio:

$$\gamma = \frac{\beta_{kk} / \beta_{kw}}{\beta_{wk} / \beta_{ww}} = \frac{\kappa_{k,kw}}{\kappa_{w,kw}}$$

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has been referred to as a 'niche differentiation' ratio. In the preceding example, say that all intraspecific competition coefficients are equal to 1, and that $\beta_{wk} = -2$, indicating that the removal of a single knapweed plant would 'make room' for two wheatgrass plants. Assuming a direct interaction, this would imply that $\beta_{kw} = -0.5$, indicating that the removal of a single wheatgrass plant would similarly 'make room' for half a knapweed plant. In such instances γ is at or very close to unity, but in situations where the two plants are using different resources (e.g., different soil profiles caused by different root system types) the niche is 'partitioned', and γ may be significantly different from unity. Thus, the above ratio provides an indication as to the 'directness' of the interaction between the two species.

Regression lines on knapweed with and without *Sclerotinia* showed a significant difference in survival rates. Regression lines on wheatgrass showed no significant difference. In addition, interspecific competition coefficients were not significantly detected, but intraspecific competition coefficients were significantly detected. The value of $\kappa_{k,kw}$ for biomass was 0.51, indicating that wheatgrass had twice the effect that knapweed had on knapweed weight. The value of γ was found to be 1.11, implying little resource partitioning, and also suggesting the intuitively reasonable notion that at high densities different species compete very directly for resources.

In summary, it was found that at high seeding densities, bluebunch wheatgrass was a more aggressive competitor than spotted knapweed, implying that increasing seeding rates of wheatgrass to high densities will improve grass establishment.

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Ecologically, the above study attempts to model a process known as "self-thinning", where plant competition results not only in biomass reductions, but also seedling mortality. The uniqueness of this study indicates that this is an area that could use significantly more study.

Lastly, as was shown to be the case for individual plant competition, much additional work in this area has focused on the simulation not only on the biomass of individual plants, but also of the growth of total species biomass. Tilman's model provides a general case, and is shown as follows.

The biomass growth model simply states that the specific growth rate of the biomass of a plant population of species *i* contains a source and a sink:

$$\frac{1}{B_i}\frac{dB_i}{dt} = f_i(R) - m_i$$

The source is a species-specific function of nutrient resources R, and the sink m_i is a biomass loss rate. The dynamics of soil nutrient resources are similarly presented in terms of a source and sink:

$$\frac{dR}{dt} = Y(R) - \sum_{j=1}^{n} Q_j B_j f_j(R)$$

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where $Y(R)$ is the nutrient supply rate, and the diversion of resources into plant species is shown in the second term, Q_j being the tissue nutrient concentration of plant species j. Usually the utilization of resources by plants is given a Michaelis-Menten feedback:

$$f_i(R) = f_{i,\max} \frac{R}{r_{50,i} + R}$$

and the supply rate is presented as a linear function of nutrient deficiency:

$$Y(R) = r(R_{\max} - R)$$

Huisman (1994) showed that making the $f_i(R)$ purely linear as well as making the nutrient supply rate $Y(R)$ and assuming steady state soil dynamics results in another model of some popularity, Berendse's model:

$$\frac{dB_i}{dt} = \frac{1}{Q_i}\left(\frac{k_i B_i}{\sum_{j=1}^{n} k_j B_j} Y - L_i B_i\right) \qquad [3.3]$$

where the coefficients k_i govern the partitioning of resources among the n species, and L_i is the 'relative nutrient requirement' of species i, governing nutrient losses among species.

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3.3 Spatially Explicit Models

3.3.1 Horizontal Heterogeneity

The third assumption of Cousens's model from the previous chapter assumes a random placement of weeds, which, of course, even from the most casual and untrained inspections is rarely the case. However, this is not to say that Cousens's model is inapplicable to situations in which spatial heterogeneity is embraced, such as applications of precision agriculture. If all other aspects of the agronomic field are considered to be spatially homogeneous (row spacing, soil type, fertility, etc.) then it is intuitively reasonable that Cousens' model could be applied in the following fashion:

$$Y_L = \sum_{i=1}^{n} w_i Y_{L_i} = \sum_{i=1}^{n} w_i \frac{sAN_{w,i}}{1 + sN_{w,i}}$$

where a simulated field could be divided into a series of n "patches" – that is, regions within which no spatial heterogeneity in weed density is deemed to significantly exist, and that, thus, spatial weed positions within the patch could be effectively represented as random. In areas of precision agriculture, the concept of the "management unit" can be applied thus. Here $N_{w,i}$, Y_{Li}, and w_i respectively describe the weed density within the patch, proportional yield loss from within the patch, and the fraction of the field the patch comprises. Also, the patches are considered to be ordered from lowest density ($i = 1$) to highest density ($i = n$).

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Considering that weeds are oftentimes distributed in patches, Reich and Davis (2000) indicate that the weed counts within a given patch (λ_i , where $\lambda_i \in J$) would theoretically follow a distribution similar to the following negative binomial distribution:

$$\lambda_i \sim \frac{(k+\lambda-1)!}{\lambda!(k-1)!} p^k (1-p)^\lambda, \lambda = 0,1,2,...$$

where p is the mean to variance ratio of λ_i:

$$p = \frac{E\{\lambda_i\}}{\sigma^2\{\lambda_i\}}$$

where $E\{\}$ and $\sigma^2\{\}$ signify, respectively, the expectation and variance operators. Values of p less than 1 would imply aggregation. The parameter k is an additional indicator of a degree of aggregation. A k value of infinity indicates random distributions whereas lower positive values of k indicate aggregation.

A good example of an existing spatial model, one which potentially could be very useful in simulating plant invasion, was a model by Silvertown et. al. (1992). In this study

data from Thorhallsdottir (1990) was applied to a simulated grid of 40 by 40 square cells, each occupied by exactly one of a given set of species. In the latter source a matrix of replacement rates (percentage replacement by biomass) was acquired and used

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in the present study as replacement probabilities, creating a quasi-Markovian transition matrix applied to situations of varying spatial patterns. Two quantitative terms were defined in this process for each species – invasive, or the degree to which a given species invades into the other four, and invasibility, or the degree to which a given species can be invaded by the others. The species represented were *Agrostis stoloifera*, *Holcus lanatus*, *Cynosurus cristatus*, *Poa trivialis*, and *Lolium perenne*. The inclusion of space allows for the investigation of the effect of intraspecific aggregation and the influence of initial conditions on the final outcome. In particular it was found that intraspecific aggregation creates a competitive advantage for a given species, which suggests that most competition experiments overestimate the importance of competition in field communities. Rather, the results indicated that aggregation acts as a strong buffer in reducing the rate at which stronger competitors are able to exclude weaker ones. Different arrangements of monospecific bands produced very different transitory dynamics, since the spatial arrangements of each species determines when each species encounters each other, as well as the degree of interaction and how much space each occupies when contact is made.

Most significantly, community change followed trajectories that could not be deduced from a knowledge of pairwise interactions alone, thus implying a significant role played by spatial configuration.

There exists a clear application of this work, that of using this same modeling technique with real mapped data of invasive and other plant species towards a simulation

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over time of future invasion. Such simulations would have to be restricted to situations where only the listed plant species exist to any degree of competitive significance and the soil, atmospheric, and radiative conditions of Thorhallsdottir's study are closely matched. Departures from these restrictions would most likely require the kind of resource management modeling mentioned in the discussion of Sheley et al. (1996).

Moving now to an agronomic setting, most spatially explicit studies have focused on the role that tillage can potentially play in accelerating the spatial spread of a weed. In a study by Woolcock and Cousens (2000) the spread of a weed from a point source is modeled for four different weeds – *Avena spp.*, *Rapahanus raphanistrum*, *Bromus spp.*, and *Fumaria spp*. The primary state variables in this simulation effort are seedbank and seed rain, both represented as continuous functions of time and one spatial dimension, the direction of cultivation. The buried seed bank is represented here as $S(x,t)$ and the seed rain as $R(x,t)$. The following relationship is true:

$$S(x,t) = \sum_{\tau=t_0}^{t-1} R(x,\tau)(1-\mu_s)^{t-\tau}$$

where t_0 is the start time and μ_s is the annual seed bank losses, which includes losses to germination as well as to mortality. The number of seedlings g produced in the following year is:

$$G(x,t+1) = g_{new} R(x,t) + g_{old} S(x,t)$$

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where g_{new} and g_{old} allow for different germination rates of new and old seeds. In addition, note that seedling survival is assumed to be 1, appropriate only for a new weed invasion for which no control strategy is in place, or perhaps for a newly emerging tolerant weed population. This assumption can be lifted by the inclusion of a new parameter ε_H:

$$N(x,t+1) = (1-\varepsilon_H)[g_{new}R(x,t) + g_{old}S(x,t)]$$

which allows for the efficacy of an herbicide or other control program.

It is also assumed that fecundity ϕ is hyperbolic with density:

$$\phi(x,t+1) = \frac{\phi_{\max}N(x,t+1)}{1+\beta N(x,t+1)}$$

where $\phi_{\max}$ is the maximum fecundity and β is a competition parameter. An alternative form which includes the crop density is as follows:

$$\phi(x,t+1) = \frac{\phi'_{\max}N(x,t+1)}{1+\beta_1[N(x,t+1)+\beta_2 N_c]^{\beta_3}}$$

For unaided dispersal, the distribution is assumed to take on a Gaussian form:

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$$w(x, x_i, t+1) = \frac{1}{2\sqrt{\pi D}} e^{-\frac{(x-x_i)^2}{4D}}$$

where D is a dispersal parameter for seeds dispersing from a source x_i. This becomes quantitative by multiplying it by the fecundity:

$$R_N(x, x_i, t+1) = p\phi(x_i, t+1)w(x, x_i, t+1)$$

where p is the proportion of the new seeds assumed to disperse naturally on the soil surface and which do not enter the harvester. Harvester dispersal is approximated by the equation:

$$v(x, x_i, t+1) = V_x e^{-\frac{x-x_i}{V_x}}, x \geq x_i$$

where V_x is a distance parameter. Again, this becomes quantitative by multiplying it by the fecundity:

$$R_H(x, x_i, t+1) = (1-p)(1-q)\phi(x_i, t+1)v(x, x_i, t+1)$$

where q is the proportion of seeds which are retained by the harvester. Thus, the total seed rain R is calculated thus:

$$R(x, t+1) = \sum_{x_i} R_N(x, x_i, t+1) + \sum_{x_i} R_H(x, x_i, t+1)$$

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For studies of dispersal, a rule of thumb developed by Cousens and Mortimer (1995) was used for three of the species, that in species without clear dispersal adaptations, half the seed is dispersed within a distance of half the height of the plant. Seed dispersal by harvesters has been found to vary significantly among machine designs, but was set at a single value for all four species.

Despite the significant degree of estimation involved, the results appeared to be on the same scale as previous findings. Kot (1992) had indicated that the rate of spread of a species without a dormant seed bank undergoing Gaussian dispersal is equal to $\sqrt{4rD}$, where r is the intrinsic rate of population increase in the absence of dispersal. This found to also be a good approximation in this study. Studies involving k revealed that an herbicide kill rate of 80% or more is necessary for any significant reduction in the rate of spread. Rate of spread was more sensitive to dispersal than demography. Sensitivity to crop density was low. Studies of p indicate that only a small percentage (10% or more) was required to initiate a significant harvest dispersal effect, above which the sensitivity was low.

Such studies have clear applications for precision agriculture and site-specific management. Previous studies have indicated that at the coarsest scales, weed populations appear to show spatial stability, localized in particular parts of fields. At the finer scales, patches are highly mobile. The distinction in this study made between demography and dispersal characteristics is reflective of such a distinction already made

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in the literature. The dispersal parameters are comparatively unknown in the ecological literature, whereas the demographic parameters are comparatively known (Cousens and Mortimer, 1995).

In addition to predicting spatial movement, studies with such a spatial focus can also provide insight into spatial scales of mutual plant interaction, thus reaching back in particular to section 3.1. In a study by Reich, Bonham, and Metzger (1997) a Gibbsian pairwise potential model was used to study the pairwise competitive interactions among species and in particular to detect a given plant's 'competitive zone' of influence. Data from a 1.5 by 1.5 m study plot near Fort Collins, CO was collected, where the dominant grasses included blue gramma (*Bouteloua gracilis*), western wheatgrass (*Agropyron smithii*), Indian ricegrass (*Oryzopsis hymenoides*), and needle-and-thread grass (*Stipa comata*).

A Gibbsian interaction model, derived from statistical mechanics, assumes that the only determinant of competitive interaction is the relative, not absolute, location of any two plants. Some appropriate variables are as follows:

A – a finite planar region

N – number of plants in A

$X = \{X_i = (x_i, y_i) \in A, i = 1,..., N\}$

Ψ – potential energy of a given pair, $\Psi = \Psi(r_{ij})$ where $r_{ij} = |X_i - X_j|$

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Implicit also here is the assumption that the given spatial arrangement is an expression of these above defined potential energies between plants and that the observed pattern is at a state of equilibrium in which the total potential energy:

$$U_N(X) = \sum_{i \neq j}^{N} \Psi(r_{ij})$$

is minimized. The analysis involved three parameterized potential functions proposed earlier in the literature which were compared via procedures involving AIC and the maximization of likelihood.

3.3.2 Deepened Ecological Understanding

In addition to the quantitative description of *in situ* measurements of nature, spatial models can provide deeper understanding of present ecological theory. Two examples are presented.

Example 1: The Competitive Exclusion Principle. The concept of the competitive exclusion principle holds a largely theoretical, but fundamental, place in the formulations of ecology. It can be explained as follows:

If two species in the same geographic location are alike in every fashion, except that one has even a slight competitive advantage over the other (and, thus, a slightly higher population growth rate than the other), then that species will eventually exclude

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the other completely, resulting in the eventual removal of the lesser species from the niche. The theory can be demonstrated mathematically as follows:

Suppose that the population of species *i* at time *t* is denoted as $x_{i,t}$ and the annual growth rate of species *i* is denoted r_i, then the population of species *i* at any time can be expressed according to the following equation:

$$x_{i,t} = x_{i,0}(1+r_i)^t \qquad [3.4]$$

where $x_{i,0}$ denotes a starting population at time 0. If two populations exist with such dynamics (denoted species 1 and 2), then the proportion of species 1 in the niche is simply its fraction of the total:

$$\gamma_t = \frac{x_{1,t}}{x_{1,t} + x_{2,t}} \qquad [3.5]$$

where γ_t is used to denote this fraction at time *t*. Combining equations [3.4] and [3.5] together this becomes:

$$\gamma_t = \frac{x_{1,0}(1+r_1)^t}{x_{1,0}(1+r_1)^t + x_{2,0}(1+r_2)^t} = \frac{x_{1,0}}{x_{1,0} + x_{2,0}\left(\frac{1+r_2}{1+r_1}\right)^t}$$

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which alone gives a firm analytical indication of the ultimate fate of the system.

If the growth rates are identical, then the fraction in the denominator becomes 1 and the above proportion remains constant:

$$\gamma_t = \frac{x_{1,0}}{x_{1,0} + x_{2,0}} = \gamma_0$$

If, however, the growth rates are different, then the result can go one of two ways, depending on which is larger – r_1 or r_2:

$r_2 < r_1$	$r_2 > r_1$
$\lim_{t\to\infty}\left(\frac{1+r_2}{1+r_1}\right)^t = 0$	$\lim_{t\to\infty}\left(\frac{1+r_2}{1+r_1}\right)^t = \infty$
$\lim_{t\to\infty}\gamma_t = \frac{x_{1,0}}{x_{1,0}} = 1$	$\lim_{t\to\infty}\gamma_t = 0$

Thus, if species 1 has a stronger growth rate, then the ultimate fate is the exclusion of species 2. Conversely, the opposite is true if species 2 has a stronger growth rate.

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Such is the competitive exclusion principle. Described succinctly, it is that 'complete competitors cannot coexist' (Hardin, 1960). The validity, and also the applicability, of this principle has been hotly debated (Gause, 1970; Ayala, 1970), and yet here the theoretical essence of the competitive exclusion principle is proved true in a situation given some assumptions. If the premises are sound, so is the conclusion.

It is in the evaluation of the assumptions of the above theoretical construct that ecological applicability begins to be compromised, much to the benefit of earth's biodiverisity. The discussion of this can be effectively divided into two parts, each heralded by the two ambiguous phrases in Hardin's quote – 'complete competitors' and 'coexist', and in particular, it is the first of these two phrases that can be addressed via a simple modeling approach.

Let's create a simple model – one which illustrates the competitive exclusion principle. We define two state variables:

B_1: Biomass per unit area of species 1

B_2: Biomass per unit area of species 2

The degree of competitive exclusion can be measured by the degree to which one biomass outweighs the other.

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For the purposes of illustrating the above principle it is hypothesized that plant growth processes can be simplified to the acquisition of resources from the environment and allocation of such towards increased biomass:

$$\frac{dB_i}{dt} = \rho_i R B_i$$

where R is the amount of available resources and ρ_i is the combined efficiencies of both acquisition and allocation. Thus, the above equation describes the growth of either species during a small time step in the growing season. Setting the total starting resources to 1 allows for the resources at any given time in the growing season to be expressed as:

$$1 - \rho_1 B_1 - \rho_2 B_2$$

which makes the equation for growth equal to the following:

$$\frac{dB_i}{dt} = \rho_i B_i \left(1 - \rho_i B_i - \rho_j B_j\right) = \rho_i B_i - \rho_i^2 B_i^2 - \rho_i \rho_j B_i B_j$$

where the second and third terms respectively allow for intraspecific and interspecific competition.

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Thus, the process of determining the final plant biomass per unit area for each species at the end of the growing season involves numerical integration:

$$B_{i,f} = B_{i,0} + \int_{t_0}^{t_f} \left[\rho_i B_i - \rho_i^2 B_i^2 - \rho_i \rho_j B_i B_j \right] dt$$

where a starting biomass (seed size) is given to each species, and the growth of each species is modeled on a discrete-time basis. If surviving seed production per unit area is assumed to be directly proportional to biomass per unit area, then this surviving seed biomass is used as the starting biomass for the following year:

$$B_{i,0,T+1} = \lambda_i B_{i,f,T} = \lambda_i B_{i,0,T} + \lambda_i \int_{t_0}^{t_f} \left[\rho_i B_i - \rho_i^2 B_i^2 - \rho_i \rho_j B_i B_j \right] dt$$

Finally, at the end of each year's growing season a biomass preponderance proportion is calculated for species 1:

$$\gamma_{1,T} = \frac{B_{1,f,T}}{B_{1,f,T} + B_{2,f,T}}$$

We seek to plot biomass preponderance at the end of each year to measure the degree of competitive exclusion. What is interesting to note is the degree of similarity this model has to the Lotka-Volterra equations. Essentially it is a basic Lotka-Volterra approach towards a simplistic model of mechanistic plant growth and interference. What

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is different here from the preceding analysis of the Lotka-Volterra equations is that the plants are given only a finite amount of time to interact, and the degree to which they interact varies with the time in the growing season. Does this effectively complicate the rules with regards to competitive exclusion?

Based on previous theory the present model would always predict total competitive exclusion whenever $\rho_2 \neq \rho_1$. The results, however, do not agree. FIGURE 3.7 shows the results for $\rho_2 = \rho_1 = 0.1$. The actual values of each of these parameters are difficult to biologically interpret, but the results are consistent with what would be expected from the parameters being equal.

FIGURES 3.8 and 3.9 show model runs where the two species are competitively dissimilar. In each case ρ_2 is kept constant at 0.1, while ρ_1 is varied. The results show complete competitive exclusion only in the most extreme cases of competitive asymmetry. A more moderate difference in competitive ability results in a momentary instance of high exclusion lasting only a few years. Eventually the degree of exclusion dampens off to a less extreme degree of exclusion. The competitively superior species still occupies the majority of the niche, but in some cases only to a slight degree (e.g., for $\rho_1 = 0.3$ species 1 ends up occupying 57% of the niche).

Thus, the results imply that the initial findings of the competitive exclusion principle in its most fundamental form become less valid when the details of competition over time are also modeled more explicitly.

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Example 2: Plant Succession. Inasmuch as plants can be and have been categorized as "r" and "K" species (or on some part of the continuum between the above two extremes) it is theorized that plant succession dynamics can be represented largely in terms of spatially-explicit seed dispersal and plant competition. A simple spatially explicit model is, thus, constructed where two species interact – one dispersing more seeds and dispersing them spatially farther from the parent plant, and the other having a greater competitive advantage. Visually the model is illustrated in FIGURE 3.10, where for this example seed longevity is limited to the following season in an effort to accelerate any succession processes. The hypothesis tested with this model is that in a spatially explicit context, species differences in competition and seed dispersal can be sufficient to create successionary phenomena.

Seeds from two plant species are randomly dispersed onto a spatial grid, and the processes of a single season are reduced to two steps:

1. Competition – Although multiple seeds can be dispersed into a single cell, only a single plant is allowed to emerge in a single cell. Competition is represented probabilistically as the "winning" seed is chosen via a random number. A greater competitive advantage appears in the form of a greater probability attached to seeds of the given species.

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2. Seed Dispersal – A certain number of seeds from each plant are dispersed, moreso for the "r" species than for the "K" species. Two random numbers are needed for each seed to disperse, one for a direction and the other to determine a distance.

The mathematics of the seed dispersal are more simplistic, and so will be shown first. For the dispersal direction a single random number is chosen between 0 and 2π:

$$x_\theta \in [0, 2\pi)$$

For the dispersal distance an exponential probability distribution is assumed:

$$e^{-x/\lambda}$$

where the characteristic dispersal distance is regulated by the parameter λ. Since the following integral from zero to infinity is equal to 1:

$$\frac{1}{\lambda}\int_0^\infty e^{-x/\lambda}dx = 1$$

if a random number r between zero and one is chosen

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$$\frac{1}{\lambda}\int_0^{x_R} e^{-x/\lambda}dx = r \qquad r \in [0,1)$$

then a corresponding distance x_R can be chosen by manipulating the above equation:

$$\int_0^{x_R} e^{-x/\lambda}dx = r\lambda$$

to the following:

$$x_R = -\lambda \ln(1+r)$$

Thus, given the coordinates of the parent plant (x, y), then the coordinates of the seed (x', y') would be calculated via:

$$x' = x + x_R \sin x_\theta$$

$$y' = y + x_R \cos x_\theta$$

The above process is repeated according to the number of seeds afforded a plant of the indicated species.

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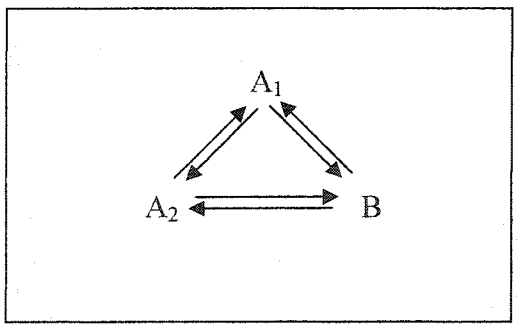
For matters of competition we first consider the simplest case of one seed from each species competing for emergence in a given grid square. Two parameters are defined:

$$\alpha = P\left(A/B\right)$$

$$\beta = P\left(B/A\right) = 1 - \alpha$$

where α is the probability that the seed from species A will prevail (notated $P\left(A/B\right)$), and β is the probability that the seed from species B will prevail (notated $P\left(B/A\right)$). Since these are probabilities, both α and β are both between zero and one, and if, for example, species A is more competitive, then α will be greater than 0.5, making β less than 0.5. The opposite will be true if species B is more competitive.



For a three seed case two of the seeds must be from the same species (say, for this example, species A). Each seed from species A is considered individually and is allowed to competitively interact will all other seeds in the grid square. The probability of either seed from species A successfully competing over the other is taken to be exactly even (0.5). Thus, the probabilities for each seed are as follows:

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$$P(A_1) = P\left(A_1/A_2\right)P\left(A_1/B\right) = 0.5\alpha$$

$$P(A_2) = P\left(A_2/A_1\right)P\left(A_2/B\right) = 0.5\alpha$$

$$P(B) = P\left(B/A_1\right)P\left(B/A_2\right) = \beta^2$$

Totaling these by species the probabilities become:

$$P(A) = \frac{P(A_1)+P(A_2)}{P(A_1)+P(A_2)+P(B)} = \frac{\alpha}{\alpha+\beta^2} \qquad P(B) = \frac{P(B)}{P(A_1)+P(A_2)+P(B)} = \frac{\beta^2}{\alpha+\beta^2}$$

Similarly for the following four seed case the probabilities become:

A_1	B_1
A_2	B_2

$$P(A_1) = 0.5\alpha^2 \qquad P(B_1) = 0.5\beta^2$$

$$P(A_2) = 0.5\alpha^2 \qquad P(B_2) = 0.5\beta^2$$

$$P(A) = \frac{\alpha^2}{\alpha^2+\beta^2} \qquad P(B) = \frac{\beta^2}{\alpha^2+\beta^2}$$

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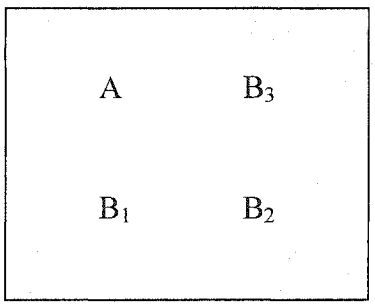
and for the following case, also with four seeds, the probabilities are as follows:



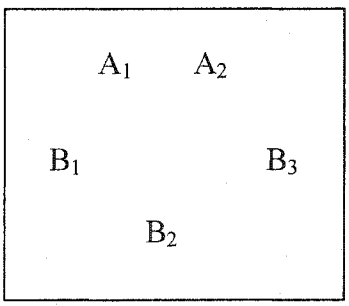
$$P(A)=\alpha^3 \qquad P(B_1)=0.25\beta$$

$$P(B_2)=0.25\beta$$

$$P(B_3)=0.25\beta$$

$$P(A)=\frac{\alpha^3}{\alpha^3+0.75\beta} \qquad P(B)=\frac{0.75\beta}{\alpha^3+0.75\beta}$$

Lastly, for the following case with five seeds the probabilities are:



$$P(A_1)=0.5\alpha^3 \qquad P(B_1)=0.25\beta^2$$

$$P(A_2)=0.5\alpha^3 \qquad P(B_2)=0.25\beta^2$$

$$P(B_3)=0.25\beta^2$$

$$P(A)=\frac{\alpha^3}{\alpha^3+0.75\beta^2} \qquad P(B)=\frac{0.75\beta^2}{\alpha^3+0.75\beta^2}$$

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Thus, for the general case involving a seeds of species A and b seeds of species B these total probabilities by species are as follows:

$$P(A) = \frac{\frac{a}{2^{a-1}}\alpha^b}{\frac{a}{2^{a-1}}\alpha^b + \frac{b}{2^{b-1}}\beta^a} \qquad P(B) = \frac{\frac{b}{2^{b-1}}\beta^a}{\frac{a}{2^{a-1}}\alpha^b + \frac{b}{2^{b-1}}\beta^a}$$

The above algorithms have been implemented via Microsoft Excel/VBA on a 100 by 100 grid with some significant results, shown in FIGURE 3.11 for different combinations of fecundity and relative competitiveness. For each plot population proportions (from zero to one) are shown for species A in light green and for species B in dark green. Simulations are made over twenty years. Different fecundity values are displayed in different rows, where in the top row species A produces eight seeds per plant as compared with two seeds per plant for species B. In the second row these fecundity values are seven and three, respectively. In the third row these values are six and four, and in the bottom row they are set equally at five for each species. Different values of relative competitiveness are displayed across different columns, where in the first column the competitiveness values are set equally at 0.5 for both species. In the second column species A is set at 0.4 compared to 0.6 for species B. In the third column these values are 0.3 and 0.7, respectively. In all cases the dispersal distance is set equally for both species at 3.5.

With the above in mind, the plot in the lower left serves as a kind of control, where the two species act identically in every way, and so their relative populations hover

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close to 0.5. Successional phenomena is defined as a temporary domination of one species over another, i.e., one's population size being temporarily larger than the other.

Instances are indeed observed where successional phenomena occurs, but two elements are required:

1. Differences in fecundity and relative competitiveness must *both* exist. In the absence of either, the population dynamics follow a permanent domination of one species.
2. These differences in fecundity and relative competitiveness must to some extent be in balance. A relatively small difference in fecundity matched with a large difference in competitiveness results in either a permanent domination or a succession event that is highly compromised at best.

These results indicate that, when modeled in a spatially explicit context, differences in fecundity and competitiveness can be enough to produce successional phenomena.

With this in mind, however, this result must be viewed with some caution. The presence of successional phenomena does not necessarily imply that differences in fecundity and competitiveness exist. A mathematician would describe the above finding by stating that differences in fecundity and competitiveness may be *sufficient* conditions for the production of successional phenomena, but they have not been demonstrated as

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necessary conditions for successional phenomena. Still, the above findings provide a clarification of theory that gives further insight into ecological understanding and provides an example of the usefulness of spatially-explicit models thus.

3.3.3 Vertical Seed Distribution

Since it has been found for numerous weed species that seed viability and emergence is a strong function of depth in the soil, it is of some use to calculate the dynamics of vertical seed movement in the soil via various tillage means as well as its effects on weed populations. The effects of crop rotation on weed population dynamics has been described in detail by an extensive body of research (e.g., Schweizer, Lybecker, and Zimdahl, 1988). What is relatively unknown, however, are the ecological mechanisms by which such weed populations are more effectively controlled. These may involve environmental impacts on the demography of weed plants (survival or fecundity) or of weed seed banks (mortality or germination). For example it has been shown by (Forcella and Lindstrom, 1988) that on some soils weed seed burial rates may be lower in a corn-soybean rotation than in continuous corn, because soybeans appear to alter the soil texture such that fewer deep soil cracks are formed. Nearer the surface the seeds are exposed to more of the biotic and abiotic mortality factors operating near the surface.

In a work by Jordan et al. (1995) a population projection model was created that permits detailed simulation of effects on weed seed banks arising from environmental differences among rotation years. The focus on weed seed banks was in recognition that

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seed bank processes often play a strong role in regulating weed populations. In addition the model is spatially explicit in depth in recognition of the effects that cultivation has on vertical seed distributions (Cousens and Moss, 1990). Two seed species were chosen, one known for longevity – *Abutilon theophrasti* – and the other known as being more transient – *Setaria veridis*.

The model structure allowed for the simulation of plants as well as seeds at three layers:

$$\mathbf{p} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix}$$

where p_1 describes plant populations and p_2 through p_4 describe seed populations at increasing soil depths. The model proceeds essentially as an event-based model, representing each event in a given agronomic year (tillage, planting, germination, harvest, etc.) as a sequence of matrix operations on **p**.

The survival function that was used involved explicit density dependence:

$$s(p_{ij}) = A_{ij} - B_{ij}e^{C_{ij}p_{ij}}$$

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where A, B, and C are constants for the i^{th} component over the j^{th} period of time. Thus, the transition matrix for germination and survival for the k^{th} rotation year is expressed as follows:

$$\mathbf{G}_k = \begin{bmatrix} 0 & g & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \\ 0 & 0 & 0 & s_4 \end{bmatrix}$$

Effects of the l^{th} tillage event are expressed as follows:

$$\mathbf{T}_l = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & t_{22l} & t_{23l} & t_{24l} \\ 0 & t_{32l} & t_{33l} & t_{34l} \\ 0 & t_{42l} & t_{43l} & t_{44l} \end{bmatrix}$$

Lastly, seed production is modeled with explicit density-dependence:

$$r(p_1) = De^{-Ep_1}$$

This model was applied towards the long-term simulation of various crop rotations on population dynamics of two different weed species as well as the identification of relevant events and processes that played a significant role in those dynamics.

The results were as follows:

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1. Continuous corn rotations resulted in sharp seed bank increases.

2. Such sharp seed bank increases were thwarted by the inclusion of soybean and/or oat/clover years. Control opportunities afforded by these crops appear critical in particular to management of *A. theophrasti*. During the oat/clover year, frequent mowing may be a significant factor.

3. For both species, winter upper-seedbank survivorships were the most influential parameters. This finding underscores the importance of implementing strategies that reduce survival of overwintering seed, such as residue burning or delayed tillage.

4. In addition, seed survivorships over the time interval between discing and field cultivation before soybean planting were also highly influential. This effect implies the effectiveness of repeated cultivation to reduce the seed bank during this period.

5. Interestingly enough, each of the above processes were more influential than per-plant seed production and plant survival. This, of course, underscores the importance of weed control measures specifically aimed at the seed bank.

6. Germination rates were found to be moderately influential, implying a weed control value of management practices that minimize germination rates, such as suppressive cover crops.

7. Depth of moldboard plowing was also found to be moderately influential, where deeper plowing was found to decrease seed bank size. The implications for effective management here are obvious.

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Thus, it is observed from the previous example that spatially-explicit models have also operated in a vertical direction, much to the profit of agronomic research and decision-making.

3.4 Herbicide Tolerance in Weeds

FIGURE 3.12 describes the extent to which tolerance to various herbicides has been developing in agronomic weeds. Note that such increases have taken place at different rates for different herbicide classes. In an effort to safeguard the use of herbicides as an effective management tool, models have also been created to understand and predict such increases. Such models have generally taken place on two spatial scales, a large scale and a small scale. Models of each scale are described in the following sections.

3.4.1 A Grand Scale Perspective: Studies of Shaner, Gressel, and Segel

One of the significant questions involved in safeguarding the use of various herbicide products in the marketplace involves attempts at predicting the likelihood of the development of large-scale herbicide tolerance to the given product. The following mathematical discussion begins with ideas from Shaner (personal communication) and

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then augments them with ideas from Gressel and Segel (1982) followed by some additional commentary from the present author.

Let L represent the overall likelihood of the development of tolerance over a given geographic region. This region is divided into subregions which utilize the herbicide in varying degrees. Let A_0 represent the size of the area untouched by the herbicide and L_0 represent the likelihood that tolerance will already be present in such an area. In the same way, let A_n and L_n represent the size of the total area that has utilized the herbicide for n years and the likelihood of the development of tolerance in such an area, respectively. If it is known that the herbicide has had marketplace usage for N total years, then the total likelihood can be represented thus:

$$L = \sum_{n=0}^{N} A_n L_n$$

If it is assumed that the herbicide is utilized in a continuous (non-rotational) fashion, then the growth of this likelihood should grow exponentially with its degree of use:

$$L_{n+1} = rL_n$$

or,

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$$L_n = r^n L_0$$

where r represents an annual growth rate ($r > 1$). Thus, our equation for total likelihood becomes:

$$L = \sum_{n=0}^{N} A_n r^n L_0$$

or,

$$L = L_0 \sum_{n=0}^{N} A_n r^n \qquad [3.6]$$

The above equation clarifies our theoretical understanding. By far the most important factor in the development of large-scale tolerance is the exponential rate term in the summation, governed by the intrinsic rate of growth and the number of years of usage. Gressel and Segel (1982) expanded further on this intrinsic growth rate r and arrived at the following expression for this rate:

$$1 + \frac{f\alpha}{\bar{n}}$$

where f is the relative fitness of the tolerant biotype compared to the same for the susceptible biotype. (This value is usually between 0.3 and 0.5.) The variable $\bar{n}$ is the

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average seed longevity in years, where species that germinate all in the following year would have an $\overline{n}$ value of 1 year and usual values are between 2 and 5 years. Lastly, α is the selection pressure for the growth of tolerance to the herbicide. Such selection pressure for a given herbicide i can be represented thus:

$$\alpha_i = \frac{1-\widetilde{\varepsilon}_i}{1-\varepsilon_i} \qquad [3.7]$$

where ε_i and $\widetilde{\varepsilon}_i$ respectively indicate the herbicidal efficacies for the susceptible and tolerant biotypes:

$$0 \leq \varepsilon_i \leq 1$$

$$0 \leq \widetilde{\varepsilon}_i \leq 1$$

Although to the knowledge of this author such has never yet been done before, Gressel and Segel's equation can be extended for the evaluation of management options for tolerance control. First, let's define an initial population proportion γ_i that is tolerant to herbicide i, and that herbicide i is utilized in conjunction with a crop that is also tolerant to the same herbicide. (For ALS tolerance the value of this proportion γ is estimated to be about 10^{-6}, and for glyphosate tolerance this is estimated to be between 10^{-15} and 10^{-10} (Shaner, personal communication).)

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Then the following expression:

$$\gamma_i\left(1+\frac{f_i\alpha_i}{\bar{n}}\right)^{n_i}$$

describes the herbicide tolerant weed biotype population proportion that must be kept at a minimum via the use of a second herbicide *j* which is from an herbicide family utilizing a different mode of action. This proportion grows exponentially, and so the above expression gives the value of this proportion after n_i years of no tolerance management. Substituting equation [3.7] for selection pressure α_i this becomes:

$$\gamma_i\left[1+\frac{f_i\left(1-\tilde{\varepsilon}_i\right)}{\bar{n}\left(1-\varepsilon_i\right)}\right]^{n_i}$$

If a second herbicide *j* from a different mode of action than herbicide *i* is introduced into the cropping system each year, then the expression becomes:

$$\gamma_{ij}\left[1+\frac{f_{ij}\left(1-\tilde{\varepsilon}_{ij}\right)}{\bar{n}\left(1-\varepsilon_{ij}\right)}\right]^{n_{ij}}$$

where now the dual subscripts "*ij*" on the variables *f*, *n*, γ, and $\tilde{\varepsilon}$ denote characteristics for the biotype having tolerance to both herbicides *i* and *j*. Now the objective is to express the variables in the above equation in terms of such variables for either herbicide *i* or *j*.

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Assuming random mating, no additional mutation or gene flow from the crop, and that the genetic variations associated with tolerances to the two herbicides are not covariant or mutually exclusive, then the starting proportion tolerant to both herbicides would be equal to the product of the proportions of tolerances to each individual herbicide:

$$\gamma_{ij} = \gamma_i \gamma_j$$

In addition, the following relationships involving herbicidal efficacies essentially state that the proportion surviving both treatments is equal to the product of the proportions surviving each individual treatment:

$$1 - \varepsilon_{ij} = (1 - \varepsilon_i)(1 - \varepsilon_j)$$

$$1 - \tilde{\varepsilon}_{ij} = (1 - \tilde{\varepsilon}_i)(1 - \tilde{\varepsilon}_j)$$

since it is assumed that one herbicide will act on the escapes of the other.

Thus, the above equation for the system involving both herbicides becomes:

$$\gamma_i \gamma_j \left[1 + \frac{f_{ij}(1 - \tilde{\varepsilon}_i)(1 - \tilde{\varepsilon}_j)}{\bar{n}(1 - \varepsilon_i)(1 - \varepsilon_j)} \right]^{n_{ij}}$$

and provides an expression for the value of the population proportion of biotypes tolerant to both herbicide i and j after n_{ij} years of continuous usage of the dual herbicide system.

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The dynamics of the above model are illustrated in FIGURE 3.13, where parameter values are set to the following:

$$\overline{n} = 5$$

$$\gamma_i = 1 \times 10^{-10} \qquad \gamma_j = 1 \times 10^{-10}$$

$$f_i = 1 \qquad f_{ij} = 1$$

$$\widetilde{\varepsilon}_i = 0 \qquad \widetilde{\varepsilon}_j = 0$$

$$\varepsilon_i = .90 \qquad \varepsilon_j = .90$$

which essentially translate into an instance of two herbicides displaying tolerance dynamics similar to glyphosate, where indigenous tolerant proportions are estimated at 10^{-10}, fitness costs are negligible, tolerant biotypes show very significant tolerance ($\widetilde{\varepsilon} = 0$), and herbicidal efficacies are approximately 90%. In addition, these results are shown for a species with a seed bank longevity of five years, certainly within the realm of reason for many species.

In the figure the dynamics of large-scale tolerance in the one and two herbicide systems are displayed together. Note that for the two herbicide system the indigenous proportion of tolerance is visible as a much lower proportion than for the one herbicide system ($10^{-10} \times 10^{-10} = 10^{-20}$). In addition, the larger selection pressure of the two herbicide system is observable in the enhanced steepness of the second line.

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The results are disconcerting in that they imply that the introduction of herbicide *j* has in this instance resulted in a loss of sustainability to the system, where instead of observable large-scale tolerance (proportions greater than 5%) occurring after 19 years, now such phenomena is observed after only 15 years! This new sustainability can be calculated by setting the expression for the tolerance dynamics of the two herbicide system equal to the analogous expression for the one herbicide system:

$$\gamma_i\left[1+\frac{f_i(1-\tilde{\varepsilon}_i)}{\bar{n}(1-\varepsilon_i)}\right]^{n_i}=\gamma_i\gamma_j\left[1+\frac{f_{ij}(1-\tilde{\varepsilon}_i)(1-\tilde{\varepsilon}_j)}{\bar{n}(1-\varepsilon_i)(1-\varepsilon_j)}\right]^{n_{ij}}$$

and solving the above equation for n_{ij}:

$$n_{ij}=\frac{n_i\ln\left[1+\frac{f_i(1-\tilde{\varepsilon}_i)}{\bar{n}(1-\varepsilon_i)}\right]-\ln\gamma_j}{\ln\left[1+\frac{f_{ij}(1-\tilde{\varepsilon}_i)(1-\tilde{\varepsilon}_j)}{\bar{n}(1-\varepsilon_i)(1-\varepsilon_j)}\right]} \qquad [3.8]$$

FIGURE 3.14 shows the same with the efficacy of herbicide *j* reduced to 60%. Certainly this is a very light herbicide application, but note that for this instance the selection pressure has been reduced for the two herbicide system such that sustainability is increased from 19 years to 25 years. Clearly this implies that not only is there no infinitely sustainable system, but also that an efficacy threshold exists for the second herbicide to even enhance such sustainability.

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This threshold can be derived by solving equation [3.8] for ε_j after setting n_{ij} equal to n_i. This results in the following equation for this threshold efficacy for herbicide j:

$$\varepsilon_{j,\max} = 1 - \frac{f_{ij}\left(1-\widetilde{\varepsilon}_i\right)\left(1-\widetilde{\varepsilon}_j\right)}{\overline{n}\left(1-\varepsilon_i\right)\left[\dfrac{1+\dfrac{f_i\left(1-\widetilde{\varepsilon}_i\right)}{\overline{n}\left(1-\varepsilon_i\right)}}{\sqrt[n_i]{\gamma_j}}-1\right]}$$

where it is defined as a maximum efficacy above which the addition of herbicide j no longer results in an increase in sustainability. This relationship is graphed in FIGURE 3.15, where more permissive thresholds are observed for higher efficacies of herbicide i, due largely to the fact that for higher efficacies of herbicide i the sustainability of the one herbicide system is shorter, and so it is only under an increasingly limited set of circumstances that the sustainability can be further lowered by herbicide j.

These results speak strongly to the potential benefits of not applying herbicide j every year, but staggering it every other year or perhaps even less often. Staggering it every other year reduces by half the number of years in which selection pressures are applied to the dual-tolerant biotype:

$$\gamma_i\gamma_j\left[1+\frac{f_{ij}\left(1-\widetilde{\varepsilon}_i\right)\left(1-\widetilde{\varepsilon}_j\right)}{\overline{n}\left(1-\varepsilon_i\right)\left(1-\varepsilon_j\right)}\right]^{n_{ij}/2}$$

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and staggering it by an arbitrary number of years (m) results in the dynamics represented by the following general expression:

$$\gamma_i \gamma_j \left[1 + \frac{f_{ij}(1-\tilde{\varepsilon}_i)(1-\tilde{\varepsilon}_j)}{\bar{n}(1-\varepsilon_i)(1-\varepsilon_j)} \right]^{n_{ij}/m}$$

This increases the sustainability of the system by the multiple m:

$$n_{ij} = m \frac{n_i \ln\left[1 + \frac{f_i(1-\tilde{\varepsilon}_i)}{\bar{n}(1-\varepsilon_i)}\right] - \ln\gamma_i}{\ln\left[1 + \frac{f_{ij}(1-\tilde{\varepsilon}_i)(1-\tilde{\varepsilon}_j)}{\bar{n}(1-\varepsilon_i)(1-\varepsilon_j)}\right]} \qquad [3.9]$$

and modifies the expression for the threshold efficacy for herbicide j thus:

$$\varepsilon_{j,\max} = 1 - \frac{f_{ij}(1-\tilde{\varepsilon}_i)(1-\tilde{\varepsilon}_j)}{\bar{n}(1-\varepsilon_i)\left\{\left[1 + \frac{f_i(1-\tilde{\varepsilon}_i)}{\bar{n}(1-\varepsilon_i)}\right]^m \Big/ \sqrt[m]{\gamma_i} - 1\right\}} \qquad [3.10]$$

FIGURE 3.16 shows the same result as in FIGURE 3.15 but with additional results for staggered applications of herbicide j. The figure indicates that even with small degrees of staggering ($m = 2$, $m = 3$) the maximum threshold efficacies are found to be significantly less restrictive.

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The fact that herbicidal efficacies are bounded at a maximum does support an existing ecological theory known as the "Refugia Concept" (Shaner, personal communication), which hypothesizes that weed shifts can be abated by keeping selection pressures at bay. In other words, strategically a kind of "safe site" must be conceded in short-term weed control in order to prevent long-term undesirable results.

Confirmation of this concept is noteworthy. It implies that the popular management practice of creating a completely clear field with absolutely no weeds is an agronomic practice for which sustainability cannot be guaranteed. The fact that the above model does not include a *de novo* mutation rate or the processes of gene flow does not mitigate this finding, since these additional processes would most likely result in relatively minor adjustments in the growth rate of large-scale tolerance.

In contrast, it implies that the use of a second herbicide can potentially be an effective technique for abating large-scale tolerance, but only if its application is staggered ($m > 1$) and its efficacy (ε_j) limited so as to be not too excessive. Either way, this would allow for the existence of a very small weed population *a la* "refugia" unless one would involve an additional non-herbicidal means of weed control (e.g., hand pulling), which would manually transcend the above mathematics and directly control indigenous presence of tolerant biotypes (γ).

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3.4.2 A Local Perspective: Studies of Powell, Maxwell, Roush, and Radosevich

FIGURE 3.17 from VanGessel (2001) shows an example of a typical herbicide dose response curve, showing a typical log-logistic curve between herbicide dose and efficacy. In reference to conversations with Powell (personal communication) it can be hypothesized that this is indicative of different degrees of herbicide tolerance among different species genotypes. With this in mind, any herbicide application will favor the more tolerant genotypes resulting in a modification of this genotype distribution in the following season. Changes in this genotype distribution would manifest themselves in a dose response curve that is shifted to the right. This shift is referred to as "rate creep". This rate creep can be modeled to some extent in the following example (with apologies to Powell since this relatively simplistic example ignores the role of gene flow).

Before working with a distribution of genotypes, we consider a case with two genotypes, alike in every way except for a difference in herbicide tolerance. We define the variables S_t and $\widetilde{S}_t$ to define the seed bank populations at year t for the susceptible and tolerant biotypes, respectively. For the susceptible biotype a certain proportion, α, of the seed bank will emerge in a given year. This corresponds to the following number of plants:

$$\alpha S_t$$

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which after an herbicide application with efficacy ε would have the following number of survivors:

$$(1-\varepsilon)\alpha S_t$$

These survivors, when multiplied by a per-plant fecundity, ϕ, would produce the following amount of seed rain:

$$\phi(1-\varepsilon)\alpha S_t$$

which, when including an overwintering survival, σ_o, becomes the following addition to the seed bank:

$$\sigma_o\phi(1-\varepsilon)\alpha S_t$$

The proportion remaining in the seed bank:

$$(1-\alpha)S_t$$

when given a survival rate of σ_s, will result in the following seeds remaining:

$$\sigma_s(1-\alpha)S_t$$

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This results in the following equation for the seed bank of the following year:

$$S_{t+1} = \sigma_o \phi (1-\varepsilon)\alpha S_t + \sigma_s (1-\alpha) S_t \qquad [3.11]$$

and an analogous equation for the tolerant biotype:

$$\tilde{S}_{t+1} = \sigma_o \phi (1-\tilde{\varepsilon})\alpha \tilde{S}_t + \sigma_s (1-\alpha) \tilde{S}_t \qquad [3.12]$$

where $\tilde{\varepsilon}$ is the efficacy of the herbicide on the tolerant biotype. With this in mind, the total species efficacy experienced by the grower can be calculated as follows:

$$\varepsilon_{T\,t} = \frac{\varepsilon S_t + \tilde{\varepsilon}\tilde{S}_t}{S_t + \tilde{S}_t} \qquad [3.13]$$

and the same for the following year is:

$$\varepsilon_{T\,t+1} = \frac{\varepsilon S_{t+1} + \tilde{\varepsilon}\tilde{S}_{t+1}}{S_{t+1} + \tilde{S}_{t+1}} \qquad [3.14]$$

Substituting equations [3.11] and [3.12] into equation [3.14] this becomes:

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$$\varepsilon_{T,t+1} = \frac{\varepsilon\left[\sigma_o\phi(1-\varepsilon)\alpha S_t + \sigma_s(1-\alpha)S_t\right] + \tilde{\varepsilon}\left[\sigma_o\phi(1-\tilde{\varepsilon})\alpha\tilde{S}_t + \sigma_s(1-\alpha)\tilde{S}_t\right]}{\sigma_o\phi(1-\varepsilon)\alpha S_t + \sigma_s(1-\alpha)S_t + \sigma_o\phi(1-\tilde{\varepsilon})\alpha\tilde{S}_t + \sigma_s(1-\alpha)\tilde{S}_t}$$

Using equation [3.13] this becomes:

$$\varepsilon_{T,t+1} = \frac{\sigma_o\phi\alpha\varepsilon_{T,t}\left(S_t + \tilde{S}_t\right) + \sigma_s(1-\alpha)\varepsilon_{T,t}\left(S_t + \tilde{S}_t\right) - \sigma_o\phi\alpha\left(\varepsilon^2 S_t + \tilde{\varepsilon}^2\tilde{S}_t\right)}{\sigma_o\phi\alpha\left(S_t + \tilde{S}_t\right) - \sigma_o\phi\alpha\varepsilon_{T,t}\left(S_t + \tilde{S}_t\right) + \sigma_s(1-\alpha)\left(S_t + \tilde{S}_t\right)}$$

or,

$$\varepsilon_{T,t+1} = \frac{\left[\sigma_o\phi\alpha + \sigma_s(1-\alpha)\right]\varepsilon_{T,t} - \sigma_o\phi\alpha\left(\dfrac{\varepsilon^2 S_t + \tilde{\varepsilon}^2\tilde{S}_t}{S_t + \tilde{S}_t}\right)}{\sigma_o\phi\alpha(1-\varepsilon_{T,t}) + \sigma_s(1-\alpha)} \qquad [3.15]$$

which is an equation that governs the slow reduction in herbicide efficacy as the herbicide slowly selects for the tolerant biotype. Again, with the addition of gene flow into the model this rate of change in efficacy could be modified in either direction. For example, if the tolerance trait involves a single base-pair manipulation (as is the case with ALS tolerance) then if the tolerance trait is dominant, then the rate of change would be faster than that indicated by equation [3.15]. For a recessive tolerance trait, then the rate of change would be slower than that indicated by equation [3.15].

Returning to FIGURE 3.17, we ask how the above technique could be applied to a more complex situation where multiple biotypes exist with varying degrees of tolerance.

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Such would be represented by a distribution of efficacies listed as a function of herbicide rate:

$$\varepsilon_t(H)$$

where H is the herbicide rate. The derivative of this function would give a population distribution of biotypes:

$$n_t(H) = \frac{d\varepsilon_t(H)}{dH}$$

where for each H the function $n_t(H)$ gives the population of all biotypes that would require an herbicide rate of H in order to be controlled. Therefore, if an herbicide application is made at a rate of H_A, then the total number of plants controlled would be:

$$\int_0^{H_A} n_t(H)dH$$

and the total number of plants not controlled would be:

$$\int_{H_A}^{\infty} n_t(H)dH$$

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Thus, in this context for each herbicide rate H the populations for the next year reflect the dynamics of the previous example under either complete control or no control:

$$n_{t+1}(H) = \lambda n_t(H) \qquad \text{where} \quad \lambda = \begin{cases} \sigma_s(1-\alpha) & H \le H_A \\ \sigma_s(1-\alpha) + \sigma_o \phi \alpha & H > H_A \end{cases}$$

where the expression $\sigma_s(1 - \alpha)$ represents a minimum growth rate (maximum decline rate) under complete control, and the expression $\sigma_s(1 - \alpha) + \sigma_o \phi \alpha$ represents unabated seed production under situations of no control. The result would be a new population distribution that could be integrated to create a new dose response curve for the following year:

$$\varepsilon_{t+1}(H_A) = \int_0^{H_A} n_{t+1}(H)\,dH \qquad [3.16]$$

Again, considerations of gene flow would further complicate the model.

Studies have taken place to consider the role of gene flow in the proliferation of herbicide tolerance. Maxwell, Roush, and Radosevich (1990) generated a model that combined plant population demographics with the Hardy-Weinberg concept for gene segregation to improve present skill in predicting herbicide tolerance dynamics. The model simulated the evolution, spread, and subsequent dynamics of tolerance in the presence and absence of an herbicide. The model simulations indicated two processes as key factors in the evolution and dynamics of herbicide-tolerant weed populations. They are processes that influence ecological fitness and gene flow. The model was a dual

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population model that simulated the evolution, spread, and dynamics of tolerant and susceptible genotypes.

The model assumed that the weed was an annual with a single emergence cohort and that all of its demographic coefficients were constant over time. Further, from a genetic perspective they assumed that the tolerance trait was localized to a single gene locus and utilized the Hardy-Weinberg model for inheritance dynamics.

The seed bank equations were as follows:

$$S_t = (1-\mu_s-\alpha)S_{t-1} + R_t + x_{t-1}\frac{a_s}{(x'+c_o)^{\beta_s}}\left(\frac{c_s^2}{c_o^2}\right)$$

$$\widetilde{S}_t = (1-\widetilde{\mu}_s-\widetilde{\alpha})\widetilde{S}_{t-1} + \widetilde{R}_t + \widetilde{x}_{t-1}\frac{\widetilde{a}_s}{(x'+c_o)^{\widetilde{\beta}_s}}\left(\frac{c_s^2}{c_o^2}\right)$$

where the susceptible and tolerant biotypes were modeled separately, and the tolerant genotype is indicated by the tilde above a variable or parameter. In both equations the first term on the right hand side allows for seed bank mortality (μ_s) and losses due to emergence (α). The second term is seed rain, which will be further defined later. The third term is a complex expression that covers seed immigration from a source site to the present site. FIGURE 3.18 from their source shows the spatial arrangement of these two sites, where the two sites are both circular with the centers a distance of x' from each other. All modeled populations are for the "treated" area, so both equations show seed immigration from the source population. These two areas have radii of c_o and c_s,

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respectively. These formulae for seed immigration follow a diffusion model, with genotype-specific parameters a_s and β_s. The variables x_{t-1} and $\tilde{x}_{t-1}$ represent the proportions of the source populations that are susceptible and tolerant, respectively.

The proportions of the seed bank that were susceptible and tolerant were also tracked:

$$s_t = \frac{S_t}{S_t + \tilde{S}_t} \qquad \tilde{s}_t = \frac{\tilde{S}_t}{S_t + \tilde{S}_t}$$

Since it was assumed that the tolerance trait is recessive, then the susceptible biotype was assumed to be composed of homozygous and heterozygous genotypes:

$$s_t = s_{Aa,t} + s_{AA,t}$$

where the recessive tolerance trait is represented by "*a*" and the dominant susceptible trait is denoted by "*A*". These two proportions were tracked individually:

$$s_{Aa,t} = \frac{s_{Aa,t-1}\left(S_{t-1} + \tilde{S}_{t-1}\right) + R_{t-1} + x_{Aa,t-1}\dfrac{a_s}{\left(x' + c_o\right)^{\beta_s}}\left(\dfrac{c_s^2}{c_o^2}\right)}{S_t + \tilde{S}_t} \qquad s_{AA,t} = s_t - s_{Aa,t}$$

Seedlings were also modeled separately:

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$$G_t = (1-\mu_g)\alpha S_t \qquad \tilde{G}_t = (1-\tilde{\mu}_g)\tilde{\alpha}\tilde{S}_t$$

where a self-thinning seedling mortality (μ_g) was included for both genotypes, and proportions of seedlings were similarly tracked:

$$g_t = \frac{G_t}{G_t + \tilde{G}_t} \qquad \tilde{g}_t = \frac{\tilde{G}_t}{G_t + \tilde{G}_t}$$

$$g_{Aa,t} = \frac{s_{Aa,t}}{s_t} g_t \qquad g_{AA,t} = g_t - g_{Aa,t}$$

Progression of seedlings into mature plants proceeded in a familiar fashion:

$$N_t = (1-\varepsilon_H)G_t \qquad \tilde{N}_t = (1-\tilde{\varepsilon}_H)\tilde{G}_t$$

and genotype proportions of mature plants were similarly tracked:

$$n_t = \frac{N_t}{N_t + \tilde{N}_t} \qquad \tilde{n}_t = \frac{\tilde{N}_t}{N_t + \tilde{N}_t}$$

$$n_{Aa,t} = \frac{g_{Aa,t}}{g_t} n_t \qquad n_{AA,t} = n_t - n_{Aa,t}$$

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In response to mature plants, however, pollen creation and immigration must be tracked:

$$P_t = \left(\frac{N_t}{N_t + \widetilde{N}_t}\right)\left(N_t + \widetilde{N}_t - I\right) + x_t I \qquad \widetilde{P}_t = \left(\frac{\widetilde{N}_t}{N_t + \widetilde{N}_t}\right)\left(N_t + \widetilde{N}_t - I\right) + \widetilde{x}_t I$$

where the variable I is immigrant pollen:

$$I = \frac{a_p}{\left(x' + c_o\right)^{\beta_p}}\left(\frac{c^2}{c_o^2}\right)$$

and the familiar diffusion model (with parameters a_p and β_p) was utilized again. Again, genotype proportions were tracked:

$$p_t = \frac{P_t}{P_t + \widetilde{P}_t} \qquad \widetilde{p}_t = \frac{\widetilde{P}_t}{P_t + \widetilde{P}_t}$$

$$p_{Aa,t} = \frac{n_{Aa,t}\left(N_t + \widetilde{N}_t - I\right) + x_{Aa,t} I}{N_t + \widetilde{N}_t} \qquad p_{AA,t} = p_t - p_{Aa,t}$$

and it was in the calculation of seed rain, R_t, that this information was utilized. The probability of an individual donating the recessive tolerant allele is:

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$$\rho = \frac{0.5p_{Aa,t} + k_r \tilde{p}_t}{k_r \tilde{p}_t + p_{AA,t} + p_{Aa,t}}$$

and this was used in the following equations for seed rain:

$$R_t = \left[2\rho(1-\rho)(1-f) + (1-\rho)^2(1-f) + (1-\rho)f\right] \frac{R_{\max}\left(N_t + \tilde{N}_t\right)}{\left(1 + \beta_1 N_t + \beta_2 \tilde{N}_t + \beta_3 N_c\right)^{\beta_r}}$$

$$\tilde{R}_t = \left[\rho^2(1-f) + \rho f\right] \frac{\tilde{R}_{\max}\left(N_t + \tilde{N}_t\right)}{\left(1 + \tilde{\beta}_1 N_t + \tilde{\beta}_2 \tilde{N}_t + \tilde{\beta}_3 N_c\right)^{\tilde{\beta}_r}}$$

where the proportions to the right show maximum seed rain mitigated in the denominator by intraspecific and interspecific competition. (N_c is the crop density). The expressions in the brackets are Hardy-Weinberg expressions slightly modified by the inclusion of an inbreeding coefficient *f*.

The above model is yet another good example of how models can serve as clarifications of theory, where simulation results can provide implications on which processes are the most important and deserve the most experimental attention. Inasmuch as gene flow follows spatial diffusion patterns of dispersal, inheritance involves Hardy-Weinberg dynamics, and herbicide tolerance involves a single-gene, homozygous recessive trait, then this model found that the most important elements in determining the dynamics of tolerance are relative fitness and gene flow. Effects of relative fitness are most significantly observed in FIGURE 3.19 from Maxwell, Roush, and Radosevich

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(1990), which showed the role of herbicide efficacy in the rise of tolerant populations. Here it is visible that as the herbicide efficacy becomes higher than about 80% the potential for the development of large-scale tolerance becomes much greater. With the source population exclusively set to susceptible genotypes, FIGURE 3.20 from the same authors showed the role that gene flow from an outside population can play. In the figure results are shown for different source population sizes and distances to the treated population, and it is observed that especially for physically large populations of susceptible genotypes that are nearby, large-scale tolerance can be highly mitigated. In both cases the "refugia concept" from section 3.4.1 is confirmed with some significant management implications. The preservation of some susceptible weeds either in the field or in nearby fields can powerfully abate the formation of large-scale herbicide tolerance.

3.5 Some Mechanistic Models

A good example of a highly mechanistic approach was a model generated by Dunan et. al. (1999) for the simulation of weed-crop interactions in direct seeded irrigated onion (*Allium cepa*). The model represented such competition exclusively in terms of competition for light resources, an hypothesis which was mostly supported by the results, and is a common valid assumption for irrigated cropping systems. The model was intended as a bioeconomic simulation model for decision-making in weed management. On a fundamental level the systemic model involved simulating plant growth for two species, onion and a weed species, within a single season. For both

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species increases in shoot drymass were calculated, from which increases in leaf area and leaf area index (LAI) were calculated, where the amount of LAI was then used to calculate further increases in drymass. One slight difference between the crop and weed was that prior to calculating leaf area for onion, shoot drymass must be partitioned into leaf drymass and bulb drymass, where only increases in leaf drymass can effectuate changes in leaf area and LAI. LAI is also the forum in which the effects of herbicides are indicated. Drymass was modeled with a time step of 1 day using the following:

$$B_{i,t} = B_{i,t-1} + \left(\frac{dB_i}{dt}\right)_t \Delta t$$

where $\left(\frac{dB_i}{dt}\right)_t$ was the growth rate of species i during day t, represented as follows:

$$\left(\frac{dB_i}{dt}\right)_t = \tau(\overline{T})\nu(\overline{T})\left(\frac{k_i A_i}{\sum_{j=1}^{n} k_j A_j}\right)\varepsilon R\left(1 - e^{-k_i A_i}\right)$$

where $\varepsilon R\left(1 - e^{-k_i A_i}\right)$ is a maximum growth rate mitigated by the effects of three proportions to the left, each of which is between 0 and 1. Tau (τ) is the effect of temperature, ν is the effect of phenology, and the third proportion is the effect of competition. The maximum growth rate was calculated as a product of R, the photosynthetically active radiation (taken as half the total daily radiative integral), ε, the

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radiative usage efficacy (found empirically via regressions of biomass and cumulative radiation), and an exponential light extinction expression, where k is the light extinction coefficient and I_i is the leaf area index at day i. The temperature and phenology factors were calculated from quadratic relationships to daily mean temperatures, $\overline{T}$, calculated as follows:

$$\overline{T} = \frac{T_{\max} + T_{\min}}{2}$$

For onion, after new biomass was calculated, it was partitioned between leaves and bulbs by a single partitioning parameter, α. Onion leaf growth was given as follows:

$$\alpha \frac{dB}{dt}$$

Onion bulb growth was as follows:

$$(1-\alpha)\frac{dB}{dt}$$

All of this was to calculate dry biomass. Leaf area was then calculated for onion:

$$A_t = A_{t-1} + \sigma\alpha\frac{dB}{dt} - \varsigma A_{t-1}$$

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where σ is the specific leaf area and ζ is the leaf senescence rate, and for the weed species:

$$A_t = A_{t-1} + \rho \frac{dB}{dt} - \varsigma A_{t-1}$$

where all was the same, except that ρ is the leaf area ratio and the partitioning between leaves and bulbs is absent.

Model predictions effectively corresponded to observed onion dry mass values for all agronomically realistic instances, and the simulations indicated a strong relationship between relative time of weed emergence and yield reduction curves, indicating later emerging weeds as less damaging. Sensitivity analyses indicated the strongest sensitivity of onion yield to weed k and ε values.

The model has significant decision-making value in that it allows for independent evaluations to be made throughout the cropping season. It permits evaluation of the contributions towards yield and profit made by weed community composition, crop and weed density, relative time of emergence, and time of weed removal. It is less mechanistic and more phenomenological than those described by Kropff and van Laar (1993). However, some mechanistic insight is obtained in that sufficient validation is obtained of a model which assumes that weed competition for irrigated onion is mainly if not exclusively for light. It should be noted that the relegation of weed-crop competition to mere competition for light resources is limited to situations in which no other limiting

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factors are present (i.e., irrigated and fertilized agronomics). This modeling approach was first done by Harper (1977).

With this in mind, most mechanistic models bear a strong resemblance to the above example in that they tend to focus on a single resource as a limiting factor. Most often this is light (e.g., Aikman and Benjamin, 1994), but there are also instances in which belowground factors are modeled as the limiting resource. Kropff and van Laar (1993) devote entire chapters to competition for nitrogen and water. For example, biomass growth in response to nitrogen limitation is modeled thus:

$$\frac{dB}{dt} = \left(\frac{\eta - \eta_{\min}}{\eta_{crit} - \eta_{\min}} \right) \left(\frac{dB}{dt} \right)_{\max}$$

where η is the nitrogen content of the soil, and the above equation is utilized when this content drops below a critical value η_{crit}, below which the biomass growth rate decreases in a linear fashion until the nitrogen rate reaches its minimum level $\eta_{\min}$, at which the growth is zero. Above the critical nitrogen level the above equation is not used and the biomass growth rate remains at the maximum rate.

Competition for water proceeds by the same authors in a similar fashion, except that values of soil water content must be continually updated, which involves the modeling of complex processes such as evaporation and plant transpiration.

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Examples of mechanistic models also extend into the biomass growth models already discussed at the ends of sections 3.1 and 3.2. In fact, a connection can be observed between these equations and those of Dunan's model if we perform the following manipulations:

Dunan's model can be effectively summarized with the following two equations:

$$\left(\frac{dB_i}{dt}\right)_t = \tau(\bar{T})\nu(\bar{T})\left(\frac{k_i A_i}{\sum_{j=1}^{n} k_j A_j}\right)\varepsilon R\left(1-e^{-k_i A_i}\right)$$

$$\frac{dA_i}{dt} = \sigma\alpha\frac{dB_i}{dt} - \varsigma A_i$$

where we are specifically considering onion, although a similar manipulation can be done for the weed growth equations. The two equations can be combined to form the following:

$$\frac{dA_i}{dt} = \sigma\alpha\tau(\bar{T})\nu(\bar{T})\varepsilon R\left(\frac{k_i A_i}{\sum_{j=1}^{n} k_j A_j}\right)\left(1-e^{-k_i A_i}\right) - \varsigma A_i$$

Note a mathematical similarity with equation [3.3] in section 3.2, which is a total biomass growth model for a given species. Here A_i is a somewhat-related quantity, the total leaf area index for a given species. Note that similar competition proportions exist:

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$$\left(\frac{k_i A_i}{\sum_{j=1}^{n} k_j A_j} \right)$$

In addition, the quantity $\left(1 - e^{-k_i A_i}\right)$ is analogous to the nutrient supply rate *Y(R)* in equation [3.1]. Lastly, in both cases the last term is a senescence term. Thus, a similarity in form is observed between Dunan's model for light competition and Berendse's model from section 3.2 for nutrient competition, which suggests that mechanistic plant competition modeling may be nearing a theoretical centralization.

3.6 Modeling of Perennial Species

Biennial and perennial species represent an additional modeling challenge in that in a given year survivors from weed management practices not only create seed rain for the present season, but also potentially for subsequent seasons. Although to the knowledge of the present author this has not yet been done in weed science literature, it is reasonable to assume that simulating such species would require the kinds of multi-stage models that are quite common in ecology and are illustrated schematically in FIGURE 3.21 drawn by the present author, where animals at different stages of maturity have certain probabilities of either dying or proceeding to the next stage of maturity. This type of approach also allows for differences in fecundity with each stage of development. In

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the case of modeling perennial weed species, it would also allow for age-specific differences in herbicide efficacy, fecundity, and seed viability. Population modeling would now involve the matrix techniques listed in section 2.8, where species populations at a given time would be represented by a vector of length n, where n is the maximum number of years the species can survive. Effects of different herbicides and other control measures could potentially be represented by transition matrix operations on this vector, and as before, eigenvalue and eigenvector analyses on these transition matrices could discern not only whether or not total populations are growing or declining, but also what an eventual equilibrium age structure of the species would be.

One element that becomes of some importance in studies of perennial species involves formation and proliferation of vegetative propagules. In a study by Donald (2000) an empirical relationship was detected between shoot emergence of *Cirsium arvense* and the degree-day heat sum. It is shown as follows:

$$Y = \frac{1.108}{1 + \left(\frac{X}{488.344}\right)^{-5.161}}$$

where X and Y represent the degree-day heat sum and the fractional shoot emergence, respectively:

$$x_i = \frac{T_{\max,i} + T_{\min,i}}{2} - T_{base} \qquad X = \sum_{i=1}^{n} x_i \qquad 0 \le Y \le 1$$

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where $T_{max,i}$ and $T_{min,i}$ represent the daily maximum and minimum temperatures for day i, respectfully, and T_{base} is a base temperature below which growth does not occur. Day 1 was chosen to be April 1. Validation of the model was seen with two independent data sets, one in *Triticum aestivum* ($r^2 = 0.82$) and the other in no-till fallow ($r^2 = 0.63$). Prediction appeared to be good in all instances except on the extremes of weed emergence, overestimating emergence at low emergence and underestimating emergence when emergence is high. The relationship indicates a window between 197 and 587 Celsius days, when 1% and 80% of the shoots have emerged, respectively. As a consequence, it is suggested that monitoring of shoot emergence should begin at the start of this window and control should occur prior to its end.

3.7 Emergence Modeling

Since in the previous chapter it is discussed that the relative timing of weed interference is of prime importance in representing effects on crop yield, it is of some value to be able to predict the timing of emergence of weed species. The processes involved in adequately representing emergence can be divided into three categories:

1. Overcoming of dormancy
2. Induction of germination
3. Sufficient growth to emerge from soil surface

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For a comprehensive treatment of emergence, all three factors must be considered, and, all in fact, act as mutually exclusive elements (Forcella et al., 2000).

3.7.1 Seed Dormancy

Benech-Arnold et. al. (2000) defines seed dormancy as "an internal condition of the seed that impedes its germination under otherwise adequate hydric, thermal, and gaseous conditions." Harper (1977) separates seed dormancy into three categories:

1. Innate dormancy
2. Induced dormancy
3. Enforced dormancy

The difference has been represented by the same source *a la* Shakespeare in the following manner:

"Some seeds are born dormant (innate), some seeds achieve dormancy (induced), and some seeds have dormancy thrusted upon them (enforced)."

Innate dormancy has been also referred to as 'primary' dormancy, whereas enforced dormancy has been referred to as 'secondary' dormancy, since it refers to an event which places nondormant seeds into a newfound state of dormancy.

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Regardless of the source of dormancy, the processes involved in breaking dormancy appear to center around two environmental aspects:

1. A set of conditions under which dormancy is minimized
2. A set of events necessary to break dormancy

In reference to the first aspect, a suitable range of temperatures and soil moisture contents are usually defined within which dormancy levels among seeds are minimized. For example, Bouwmeester and Karssen (1992) modeled the degree of dormancy of *Polygonum persicaria* by representing germination as a function of temperature according to a quadratic function:

$$G = aT_g^2 + bT_g + c$$

Such an equation provides a range of possible temperatures for germination.

Examples also exist for the second aspect of seed dormancy. The seeds of winter annuals require an event where the temperature exceeds a specific level in order for dormancy to be broken. Summer annuals, however, require a similar overwintering event in which the temperature drops below a specific level in order for dormancy to be broken. Other annuals, like giant foxtail (*Setaria faberi*), require events related to soil moisture (Taylorson, 1986) or a specific photoperiod event (e.g., *Avena fatua* – Armstrong and

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Adkins, 1998). In addition, other potential causal factors include pH (Susko et al., 1999) and salinity (Chachalis and Reddy, 2000).

In reference again to Bouwmeester and Karssen (1992), the coefficients *a*, *b*, and *c* were modeled as a function of cold and heat unit sums:

$$a, b, c = f(C, H)$$

This is another example of the second aspect of seed dormancy. The variables *C* and *H* describe environmental events (*C* is incremented for each period of ten days that the mean soil temperature is below a critical level of 15°C) which would have the effect of widening or narrowing the above range of possible temperatures for germination.

Future studies in dormancy may need to be extensive, for variations in innate dormancy have even been found among different biotypes of the same species (Adkins et. al., 1986). Thus, numerous studies may be necessary on the same species to achieve a full understanding.

Generally, for studies like those that follow in the next section, matters of seed dormancy must be experimentally removed. This usually done by one of three methods:

1. The exposure of the seed to acidic conditions
2. The exposure of the seed to a growth hormone (usually gibberelic acid)

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3. Physical injury of the seed to compromise its protective seed coat

3.7.2 Germination and Emergence from Surface

Whereas seed dormancy can usually be considered separately from the other two elements of emergence modeling, the latter two elements, though distinct in nature, are often considered in tandem. Experiments are conducted on seeds of a given species from which dormancy has been removed by one of the three above methods and which have been planted to various depths in the soil. Similar experiments are also done hydroponically, in which case the process of germination can be isolated from growth to the soil surface.

As was discussed in the section on vertical seed distribution, the degree of emergence for many species will depend on the depth of the seed in the soil, and the elements discussed in this section may provide some mechanistic insight into why that is so. What is of primary concern here, however, is the effective representation of the period of time within the growing season in which emergence takes place.

FIGURE 3.22, from Anderson (1994) shows the degree of new emergence plotted as a function of time in the growing season for a large community of multiple weed species and averaged over a period of seven years. The species in the community included downy brome (*Bromus tectorum*), green foxtail (*Setaria viridis*), longspine sandbur (*Cenchrus longispinus*), Stinkgrass (*Eragrostis cilianensis*), volunteer wheat

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(*Triticum aestivum*), wild-proso millet (*Panicum milaceum*), common purslane (*Capsella bursa-pastoris*), common sunflower (*Helianthus petiolaris*), horseweed (*Conyza canadensis*), kochia (*Kochia scoparia*), prostrate pigweed (*Amaranthus graecizans*), puncturevine (*Tribulus terrestris*), redroot pigweed (*Amaranthus retroflexus*), Russian thistle (*Salsola iberica*), smooth pigweed (*Amaranthus hybridus*), and wild buckwheat (*Polygonum convolvulus*). While the standard error curve shows a great deal of variation, there were some significant temporal patterns which were visible in the plant community. Kochia and Russian thistle were the main species that dominated the first emergence peak, while green foxtail, wild-proso millet, and pigweed species dominated the second peak. In addition, it was found that tillage events, while potentially changing the degree of species emergence, did not alter the emergence pattern. Instead, much of the variability was reported to be explainable from variations in precipitation timing. With this in mind, a multitude of studies have been published attempting to explain species emergence patterns as a function of environmental variables. More on this later in this section.

Weibull distributions. In a study by Brown and Mayer (1988) several methods were investigated for the representation of seed germination. In one study, six different functions were compared for describing cumulative germination of nondormant seeds. FIGURE 3.23 is from their study, where a cumulative Weibull distribution was chosen as an optimal fit.

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In a later study by Bridges et. al. (1989), Weibull distributions were fit for the germination times of red rice, rice, rice "Nato", bagpod sesbania, Drummond rattlebush, smallflower morningglory, redweed, sicklepod, hemp sesbania, and sharppod morningglory. Germination studies consisted of 5 to 7 constant temperature regimes ranging from 10 to 45 degrees Celsius. The different distributions from each temperature value were then amalgamated using a weighted average that involved scaling the time values in each distribution so that the median time value was the same. Under this new time scale (referred to as 'tau') curves of the same shape would line up identically. The process of performing this technique was mostly successful with statistical errors become increasingly significant as one went to the tails of the distribution. Once these temperature-independent distributions were acquired, however, the process of fitting the three-parameter Weibull curves to them was very successful, with R^2 values being at least 0.996 for each species. This confirmed the adequacy of the Weibull distribution for describing such distributions.

A three parameter Weibull is presented as follows:

$$f(T)=\frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \qquad [3.17]$$

where $T \geq \gamma$. It has a cumulative density function which is:

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$$F(T)=\int_{\gamma}^{T} f(t)dt=-e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}\Bigg|_{\gamma}^{T}=-e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}-(-1)=1-e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$

An example of the Weibull distribution from equation [3.17] is shown in FIGURE 3.24. The use of the Weibull shows a great deal of advantageous promise for two reasons:

1. Like the model of Cousens (1985), the parameters are biologically interpretable, and
2. Mathematical properties of the Weibull allow for some additional modeling studies to be performed easily.

As the Weibull equation is displayed above, the parameters offer the following biological interpretation:

γ indicates the time in the growing season at which emergence begins

η controls the width of the emergence curve, or the length of time in which new emergence takes place, and

β is a shape parameter which controls whether the degree of new emergence tends to occur near the beginning or the end of the emergence period.

A Model to Predict Annual Changes in Weed Emergence Patterns. The use of the Weibull offers an additional modeling tool for understanding and simulating changes in

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emergence patterns over long periods of time. An example of this is the model presented in this section. Since weed control events only produce a mortality effect on germinated seeds, it has been documented that weed control practices over time have had a selective effect on the timing of weed emergence. Mathematically this would be represented as a modification of an existing emergence curve from one year to the next. In this model, the emergence curve for a given weed species is modified based upon the results of a given singular weed control event, the timing and intensity of which can be varied. Implicitly it is assumed that a given emergence curve is solely the result of genetic diversity and that different 'emergence biotypes' are selected for based upon degree of control.

What makes this model possible is the fact that a Weibull distribution can be deduced given three conditions:

1. The point at which the distribution begins (i.e., the start of emergence) is given (t_0)
2. The point at which the distribution ends is given (t_1). This condition is more difficult, since the Weibull distribution never reaches a value of zero after the distribution begins. Thus, this is represented by the condition that the cumulative distributions will reach a value of $(1 - \varepsilon)$ at a given point in time, ε being a very small number.
3. The value of the cumulative distribution at an intermediate point (t_A) is given. $(\Omega = F(t_A))$

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Boundary condition 1 provides the following:

$$1 - e^{-\left(\frac{t_0 - \gamma}{\eta}\right)^{\beta}} = 0$$

which becomes:

$$t_0 = \gamma$$

Thus, the parameter γ is given. Boundary conditions 2 and 3 deduce the following:

$$1 - e^{-\left(\frac{t_1 - \gamma}{\eta}\right)^{\beta}} = 1 - \varepsilon \qquad 1 - e^{-\left(\frac{t_A - \gamma}{\eta}\right)^{\beta}} = \Omega$$

which respectively become:

$$\eta = \frac{t_1 - \gamma}{(-\ln \varepsilon)^{1/\beta}} \qquad \eta = \frac{t_A - \gamma}{[-\ln(1 - \Omega)]^{1/\beta}}$$

These not only provide expressions for η, but they can also be combined to form an equation for β:

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$$\frac{t_A - \gamma}{[-\ln(1-\Omega)]^{1/\beta}} = \frac{t_1 - \gamma}{(-\ln \varepsilon)^{1/\beta}}$$

which is:

$$\beta = \frac{\ln\left[\frac{\ln(1-\Omega)}{\ln \varepsilon}\right]}{\ln\left[\frac{t_A - \gamma}{t_1 - \gamma}\right]}$$

Thus, given an initial emergence curve, the emergence curve for the following year can be calculated based upon the deduction of the following four parameters:

t_0 Time that emergence begins

t_1 Time that emergence ends

t_A Point in the time of emergence that the effects of the herbicide end

Ω Proportional cumulative emergence by time t_A next year

The parameter t_0 remains the same and is set to γ. The parameter t_1 is implicitly kept semi-constant by arbitrarily setting ε to a very small constant and calculating t_1 for the following year according to the equation shown below:

$$t_1 = \eta(-\ln \varepsilon)^{1/\beta} + \gamma$$

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The value of parameter t_A is given, but Ω requires some calculation as well as some assumptions concerning the weed population dynamics. Beginning with the following equation for such dynamics, relating seed bank populations in year i to the same in the year $(i + 1)$:

$$N_{i+1} = \sigma_s \sigma_o (1-\alpha) N_i + \alpha \varepsilon F(t_A) \phi \sigma_o N_i$$

where σ_s and σ_o are, respectively, the seasonal and off-season seed survival rates. Similarly, α and ϕ represent proportional emergence and per-plant seed production. Lastly, ε and $F(t_A)$ are the proportional efficacy of the herbicide and the proportion of the weed population it effects. It is assumed that the values of all demographic parameters are constant from year to year, and, thus, that weed populations in a given year are proportional to seed bank populations in the same year via the parameter α.

The above population model acts as a suitable example of what can be used with our derived emergence distribution model. Others may be applied as well.

In addition, it is further assumed that the above demographic parameters are the same for all biotypes within the same species. Thus, the above equation can be divided into two parts:

$$N_{i+1,h} = \sigma_s \sigma_o (1-\alpha) N_{i,h} + \alpha \varepsilon F(t_A) \phi \sigma_o N_{i,h} \qquad N_{i+1,n} = \sigma_s \sigma_o (1-\alpha) N_{i,n} + \alpha \varepsilon F(t_A) \phi \sigma_o N_{i,n}$$

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where $N_{i,h}$ and $N_{i,n}$ are, respectively, populations of biotypes that do or do not receive the herbicide application. In this way all biotypes are represented as acting independently, and no mutation or gene flow is considered, only selection. The value of each of these quantities for the present year is represented by the cumulative Weibull function:

$$N_{i,h} = [F(t_A)]_i N_i \qquad N_{i,n} = \{1 - [F(t_A)]_i\} N_i$$

and the value of Ω is found by calculating the proportion of next-year's weed population that will emerge prior to t_A[3]:

$$\Omega = \frac{N_{i+1,h}}{N_{i+1,h} + N_{i+1,n}} = \frac{\sigma_s \sigma_o (1-\alpha) N_{i,h} + \alpha\varepsilon\phi\sigma_o N_{t,h}}{\sigma_s \sigma_o (1-\alpha) N_{i,h} + \alpha\varepsilon\phi\sigma_o N_{t,h} + \sigma_s \sigma_o (1-\alpha) N_{i,n} + \alpha\varepsilon\phi\sigma_o N_{t,n}}$$

This equation can be made population-independent by using the above relations for $N_{i,h}$ and $N_{i,n}$:

$$\Omega = \frac{\sigma_s \sigma_o (1-\alpha)[F(t_A)]_i N_i + \alpha\varepsilon\phi\sigma_o [F(t_A)]_i N_t}{\sigma_s \sigma_o (1-\alpha)[F(t_A)]_i N_i + \alpha\varepsilon\phi\sigma_o [F(t_A)]_i N_t + \sigma_s \sigma_o (1-\alpha)\{1 - [F(t_A)]_i\} N_i + \alpha\varepsilon\phi\sigma_o \{1 - [F(t_A)]_i\} N_t}$$

or,

[3] Admittedly this assumes that per-plant fecundity is constant for all emergence cohorts of a species, an obviously incorrect assumption that only serves as a first approximation for an admittedly cursory theoretical treatment here. In a realistic application the Weibull function would have to be multiplied by one of the fecundity weighting functions which will be derived in chapter 7.

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$$\Omega = \frac{\sigma_s\sigma_o(1-\alpha)[F(t_A)]_i + \alpha\varepsilon\phi\sigma_o[F(t_A)]_i}{\sigma_s\sigma_o(1-\alpha)[F(t_A)]_i + \alpha\varepsilon\phi\sigma_o[F(t_A)]_i + \sigma_s\sigma_o(1-\alpha)\{1-[F(t_A)]_i\} + \alpha\varepsilon\phi\sigma_o\{1-[F(t_A)]_i\}}$$

Thus, all parameters for the next year's emergence pattern can be calculated without knowing the actual plant population levels. They are simply calculated from the parameters, the only dynamic portion being the value of $[F(t_A)]_i$.

FIGURE 3.25 shows some example output from the model, beginning with a standard emergence curve for *Abutilon theophrasti* and calculating the evolution of this emergence curve over three years with a repeated post-emergence herbicide application on the same date each year. The model forecasts a significant change in the emergence pattern within a period of only 2 – 3 years, approaching what appears to be a new steady-state distribution where the preponderance of the weeds now emerging after the herbicide treatment.

One of the important questions this model raises has to do with the ultimate cause of the variability in the time of weed emergence. The above model assumes a level of genetic determinism that is almost certainly unrealistic (e.g., a seed whose parent plant emerged on April 10th can only emerge on the same date). The fact that such weed shifts are not observed to occur so rapidly suggests either that gene flow plays an important role or that environmental factors are also highly involved in the timing of weed emergence. In particular the latter element is shown to be true.

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The study of the effects of the environment on seed germination patterns carries with it not only the promise of more accurate prediction of emergence patterns for the same location in the coming year, but also more accurate prediction of emergence patterns for the same species in other geographic locations. This is covered in the next subsection.

Environmental Effects on Germination. Since for many species a dependence of seed germination rates on soil temperature has been demonstrated, oftentimes the degree of emergence has been shown plotted against cumulative thermal time, defined as follows:

$$\theta_{T,i} = \sum_{j=1}^{i} \max\left[\left(\frac{T_{j,\max} + T_{j,\min}}{2} - T_B\right), 0\right] \qquad [3.18]$$

where the thermal time on day i, $\theta_{T,i}$, is found by adding together the 'degree days' for each day from the start of the growing season ($j = 1$) to the present day ($j = i$). For each day this is found by subtracting a base temperature from the daily mean temperature:

$$\frac{T_{j,\max} + T_{j,\min}}{2} - T_B$$

where $T_{j,\min}$ and $T_{j,\max}$ are the daily minimum and maximum temperatures, respectively, and T_B is an empirically derived base temperature (found to be the temperature below

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which no additional plant emergence takes place). The daily contributions are added together to form the cumulative thermal time $\theta_{T,i}$.

The biological concept behind the formulation of thermal time is simply that the germination rate at any moment will be related to temperature. Thus, integrating both sides of such an equation would result in amount of germinated seeds related to temperature integrated over time.

Del Monte and Tarquis (1997) created such a model for *Solanum nigrum* species describing not only aspects of germination but also the breaking of dormancy.

FIGURE 3.26 is from Hartzler et al. (1999). Emergence patterns are shown for woolly cupgrass (*Eriochloa villosa*), giant foxtail (*Setaria faberi*), waterhemp (*Amaranthus rudis*), and velvetleaf (*Abutilon theophrasti*). Unlike the figure from Anderson (1994), these graphs are for only one year (1995), and the daily precipitation for that year is shown in the top plot. Note that the sporadic nature of the emergence patterns appear to some extent to proceed in response to precipitation events. With this in mind, many authors have sought to incorporate effects of precipitation and soil moisture into the modeling of germination.

FIGURE 3.27 from Blackshaw (1991) shows the effect of soil temperature and moisture on the germination percentages of downy brome, winter canola (*Brassica napus*), winter wheat, and winter rye (*Secale cerale*). In each case a dependence on both

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temperature and moisture is observed. Blackshaw (1990) has done similar studies on round-leaved mallow (*Malva pusilla*) and found that soil moisture has a strong influence on total emergence attained, while temperature has the strongest influence on the rate of emergence.

Inasmuch as thermal time is defined as a temperature variable integrated over time, a similar concept known as 'hydrotime' is defined as soil water potential integrated over time, shown as follows:

$$\theta_H(g) = [\Psi - \Psi_b(g)]t_g \qquad [3.19]$$

where in this case Ψ is soil water potential and $\Psi_b(g)$ is a base water potential below which germination of a percentage g of the population will not occur.

In both cases germination rates can be calculated by taking the reciprocal of t_g:

Thermal Time	Hydro-Time
$r_T(g) = 1/t_g = \frac{T - T_b}{\theta_T(g)}$	$r_H(g) = 1/t_g = \frac{\Psi - \Psi_b(g)}{\theta_H(g)}$

FIGURE 3.28 is from Weaver and Thomas (1986), who investigated the thermal dependence upon germination of two pigweed species – redroot pigweed (*Amaranthus retroflexus*) and powell amaranth (*Amaranthus powellii*). In addition, within each species

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two biotypes were tested, one sensitive and the other tolerant to atrazine. Germination rates are plotted as a function of temperature. For both species an optimal temperature range was observed, but for powell amaranth a difference in germination rates was observed between its sensitive and tolerant biotypes, thus providing a connection between studies of emergence and studies of herbicide tolerance.

Hydrothermal time is the amalgamation of both thermal time and hydro-time:

$$\theta_{HT} = (T - T_b)\{\Psi - \Psi_b(g)\}_g \qquad [3.20]$$

Since it is assumed that Ψ_b is normally distributed, the above equation can be expressed thus:

$$\theta_{HT} = (T - T_b)\{\Psi - [\Psi_b(50) + \rho(g)\sigma_{\Psi_b}]\}_g$$

where $\Psi_b(50)$ is the median level of the threshold and $\rho(g)$ is the number of standard deviations $\sigma_{\Psi b}$ above or below this level. To accomplish this, $\rho(g)$ is what is known as a probit transformation of g:

$$\rho(g) = probit(g)$$

The probit function has the effect of linearizing a cumulative normal distribution. For more information on the probit function, the reader is referred to Finney (1952).

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Forcella (1993) created a model for velvetleaf seedling emergence which had significant predictive success, but had slightly more complex functions for temperature and hydrological dependencies. Velvetleaf emergence G_t was defined on a daily basis (day t) and updated thus:

$$G_{t+1} = G_t + g_t\left(1 - \frac{G_t}{100}\right)$$

where it is important here to clarify that G_t is a percentage of the total seasonal emergence. The germination rate constant g_t was also calculated on a daily basis based upon soil temperature and moisture:

$$g_t = g_{temp,t}\, g_{H_2O,t}$$

$$g_{temp,t} = 1.3e^{-\frac{(\bar{T}_s - 20)^2}{125}} \qquad g_{H_2O,t} = 1.971e^{-\frac{(P-0.6457)^2}{0.6354}}$$

where T_s and P are, respectfully, the average soil temperature and soil water potential. These were both updated based upon daily measurements of temperature and rainfall and estimates of evaporation.

Studies of emergence appear to be one of the more prolific areas of study in the scientific literature, and such models are presently providing strong predictive success to

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the general public (Comis, 1997). In addition, more study on this topic could clearly take place, for as is the case with dormancy, dependencies of germination on salinity, pH, and light have also been detected (Chachalis and Reddy, 2000).

3.8 Summary

Weed science is a good example of a scientific field that has embraced an eclectic interdisciplinary set of concepts and tools, from the field of statistics which actually originated in agronomic field studies, to techniques of genetics and plant biochemistry involved in studies of herbicide tolerance and mode of action, to the set of agronomic skills necessary to design studies and interpret results in a fashion that is savvy to the needs of growers and crop consultants, to laboratory analytical chemistry skills necessary to investigate plant biomass reductions and herbicide translocation. This chapter described in particular the results of a growing embrace of techniques in particular from the field of ecology, where the kinds of mathematical treatments and simulation models are more common. Such techniques have included a more intense theoretical investigation and modeling of the dynamics of plant biomass, interference, emergence, growth, seed dispersal, and spatial proliferation.

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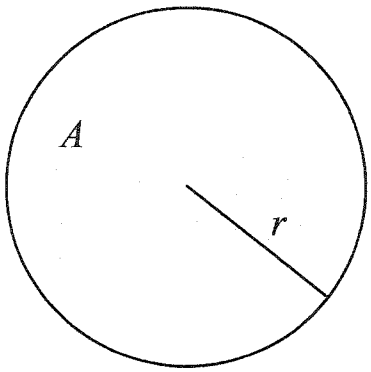

FIGURE 3.1, A theorized horizontal area of competitive influence for a single plant. The area is circular with radius r and area A.

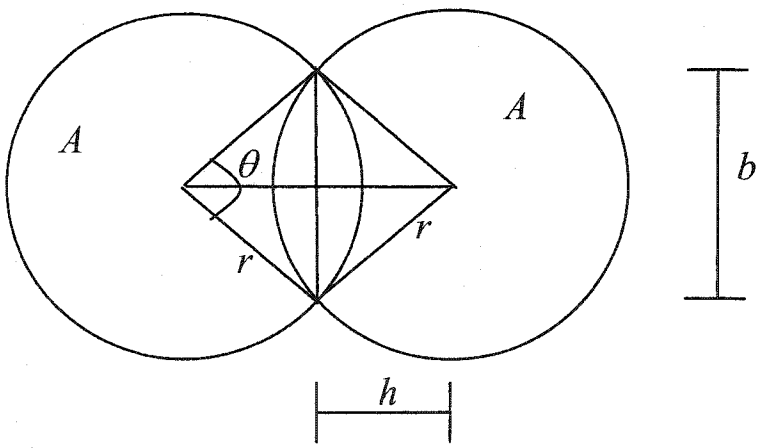

FIGURE 3.2, The geometry of two plants whose horizontal areas of competitive influence are overlapping.

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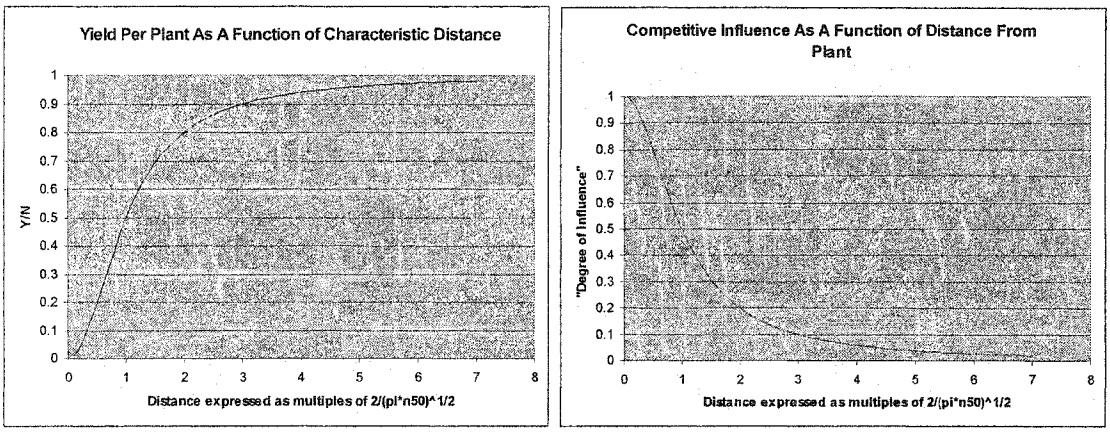

FIGURE 3.3, Yield per plant as a function of average distance to the nearest neighbor, and competitive influence shown as a function of distance.

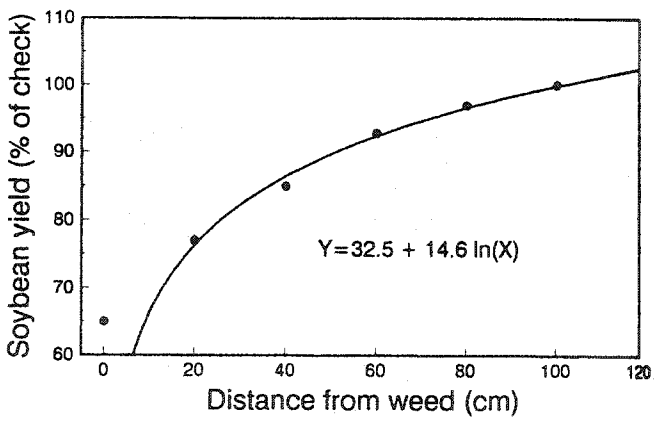

FIGURE 3.4, from Pike et. al. (1990), showing per-plant soybean yield as a function of distance to common cocklebur or jimsonweed.

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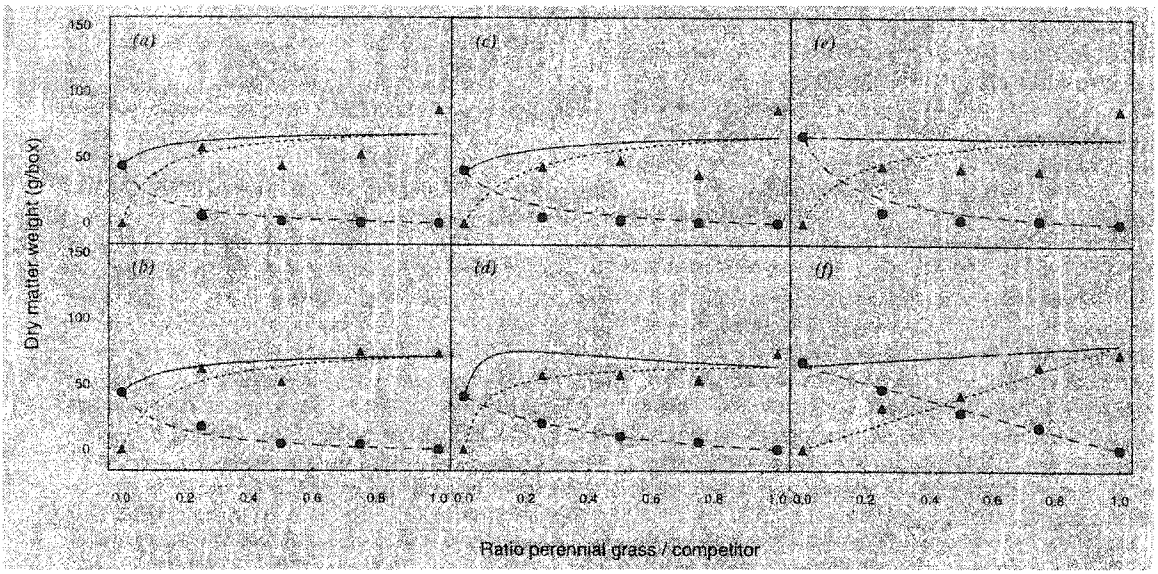

FIGURE 3.5, from Lodge (2000), showing fitted replacement series diagrams for perennial grass dry weight (g/box, dashed line) and competitor dry weight (g/box, dotted line) along with total dry weight (g/box, solid line) at 216 days after sowing. Data are for (a) *D. linkii* and annual ryegrass, (b) *D. linkii* and white clover, (c) *D. richardsonii* and annual ryegrass, (d) *D. richardsonii* and white clover, (e) *P. aquatica* and annual ryegrass, and (f) *P. aquatica* and white clover. Mean data points for the perennial grass and competitor are indicated by triangles and circles, respectively. Lines were fitted to all data.

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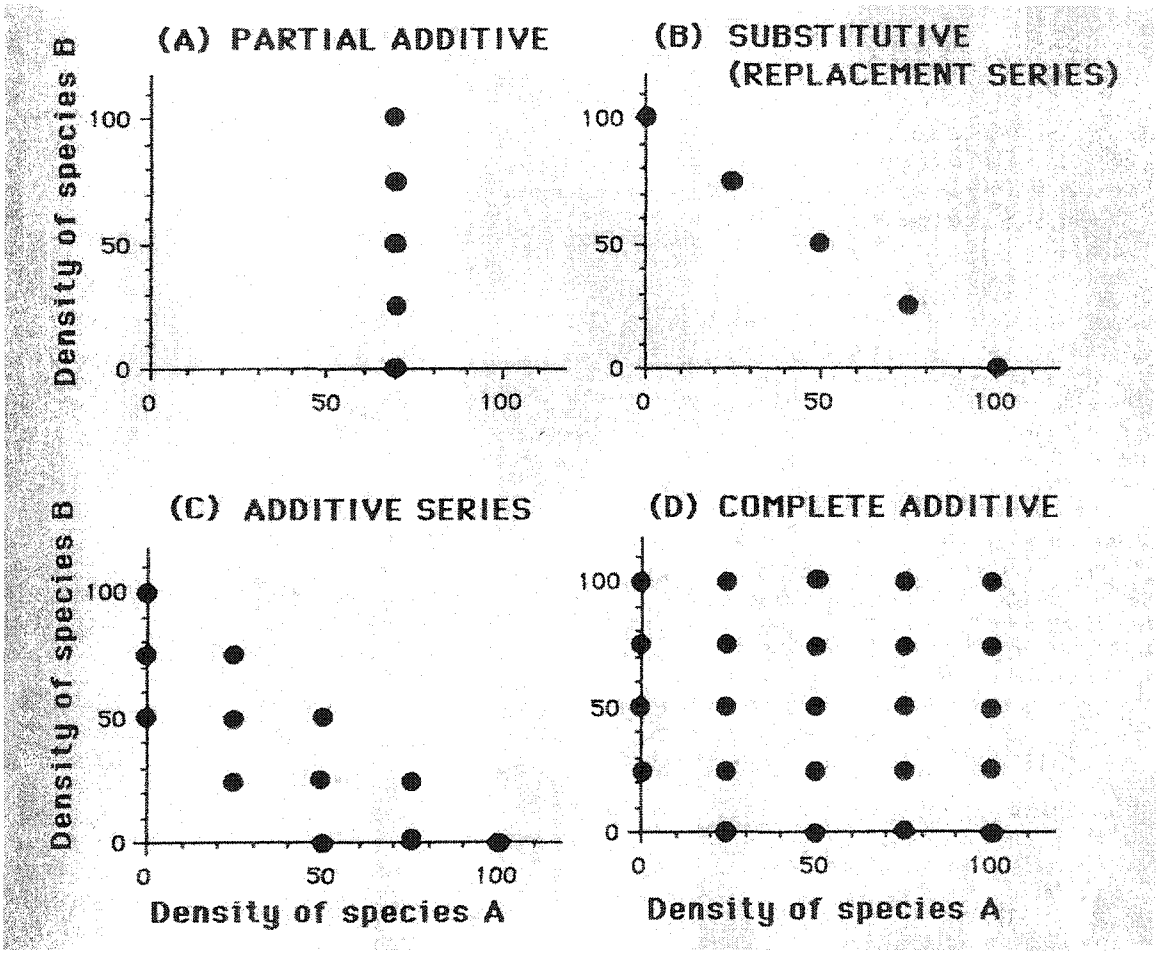

FIGURE 3.6, from Rejmanek et al. (1989), showing four basic designs for competition experiments.

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$\rho_2 = \rho_1 = 0.1$

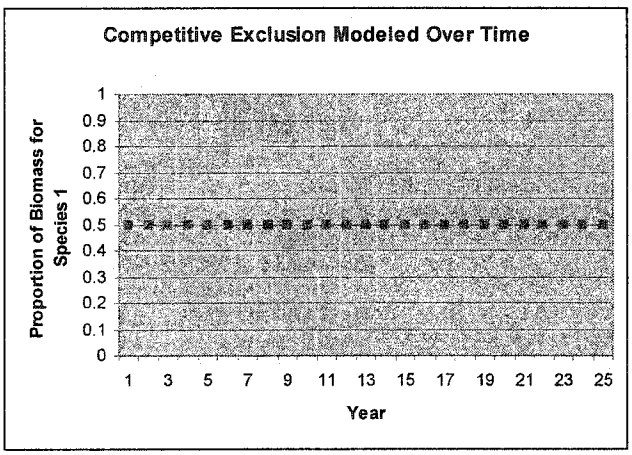

FIGURE 3.7, Model results for two competitively equal species.

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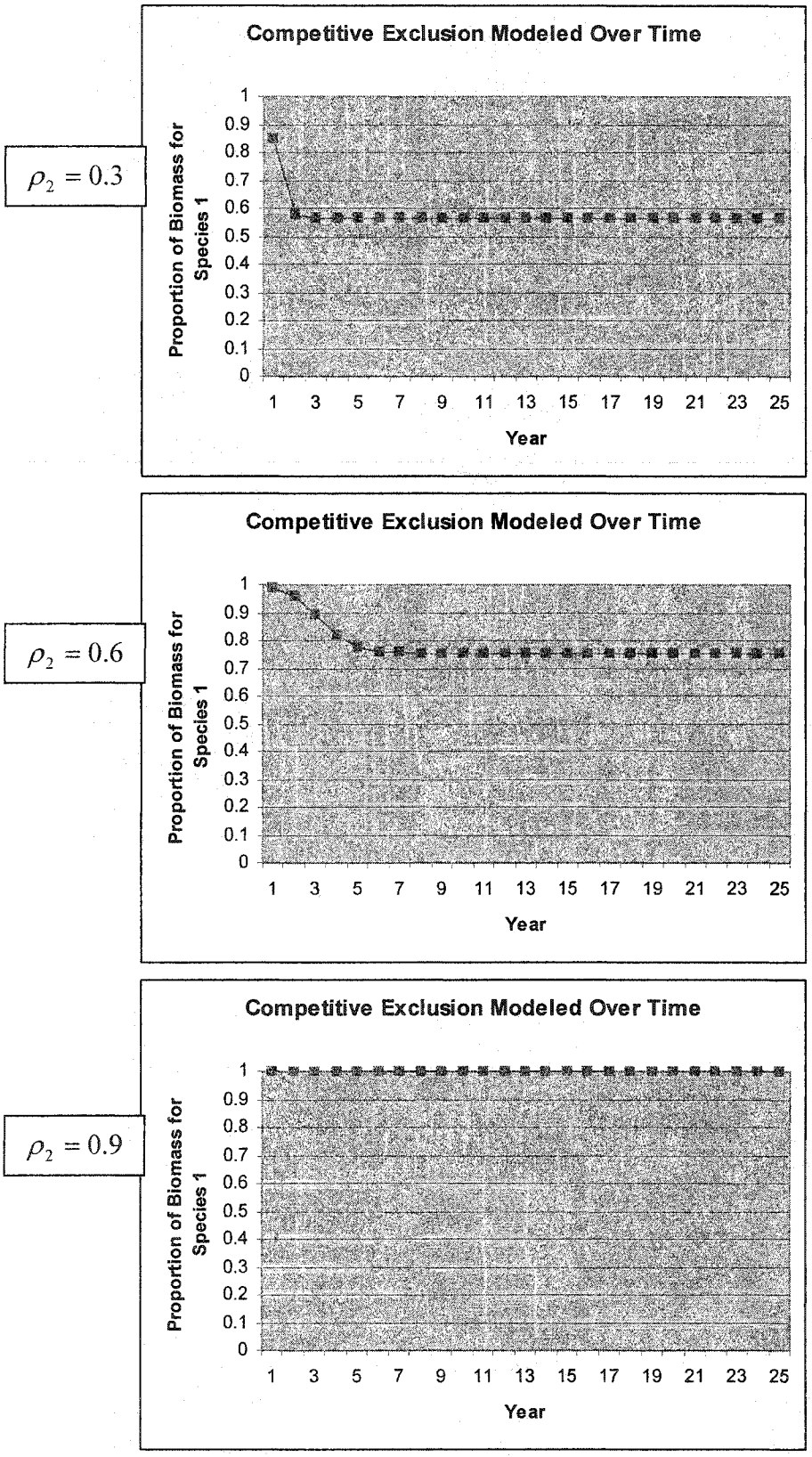

FIGURE 3.8, Model results for instances where species 1 is competitively superior.

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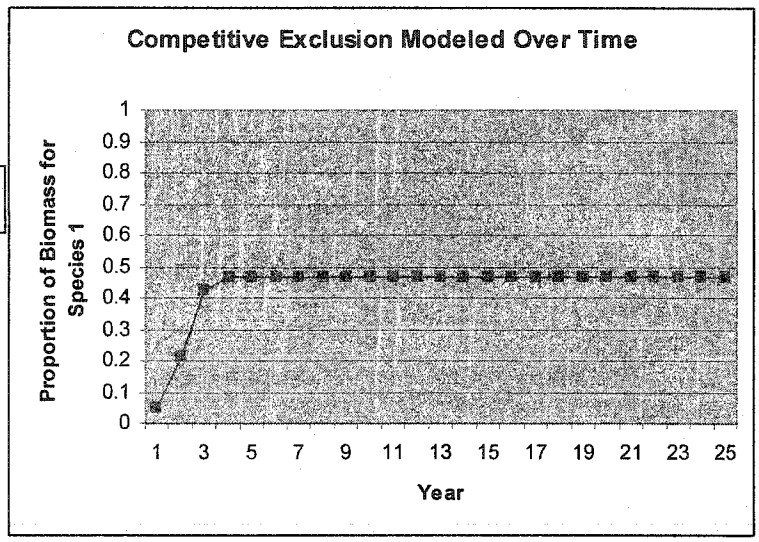
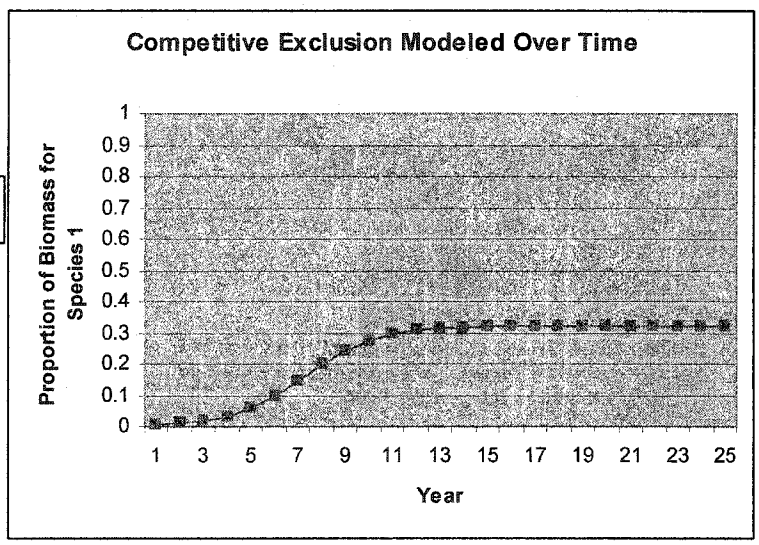
$\rho_2 = 0.06$



$\rho_2 = 0.04$



$\rho_2 = 0.02$

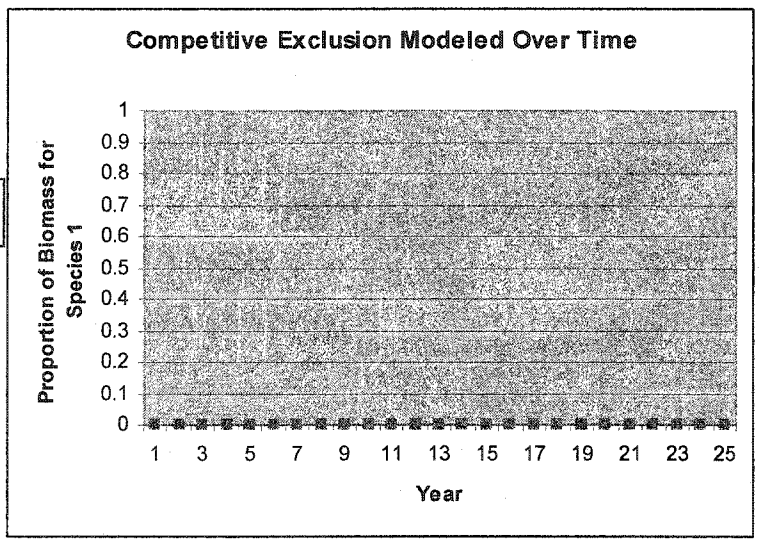


FIGURE 3.9, Model results for instances where species 2 is competitively superior.

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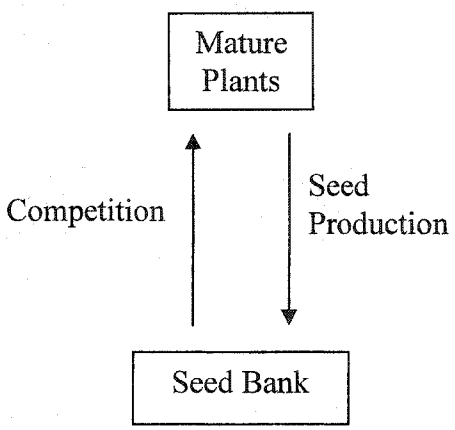

FIGURE 3.10, schematic diagram of plant succession model described in section 3.3.2.

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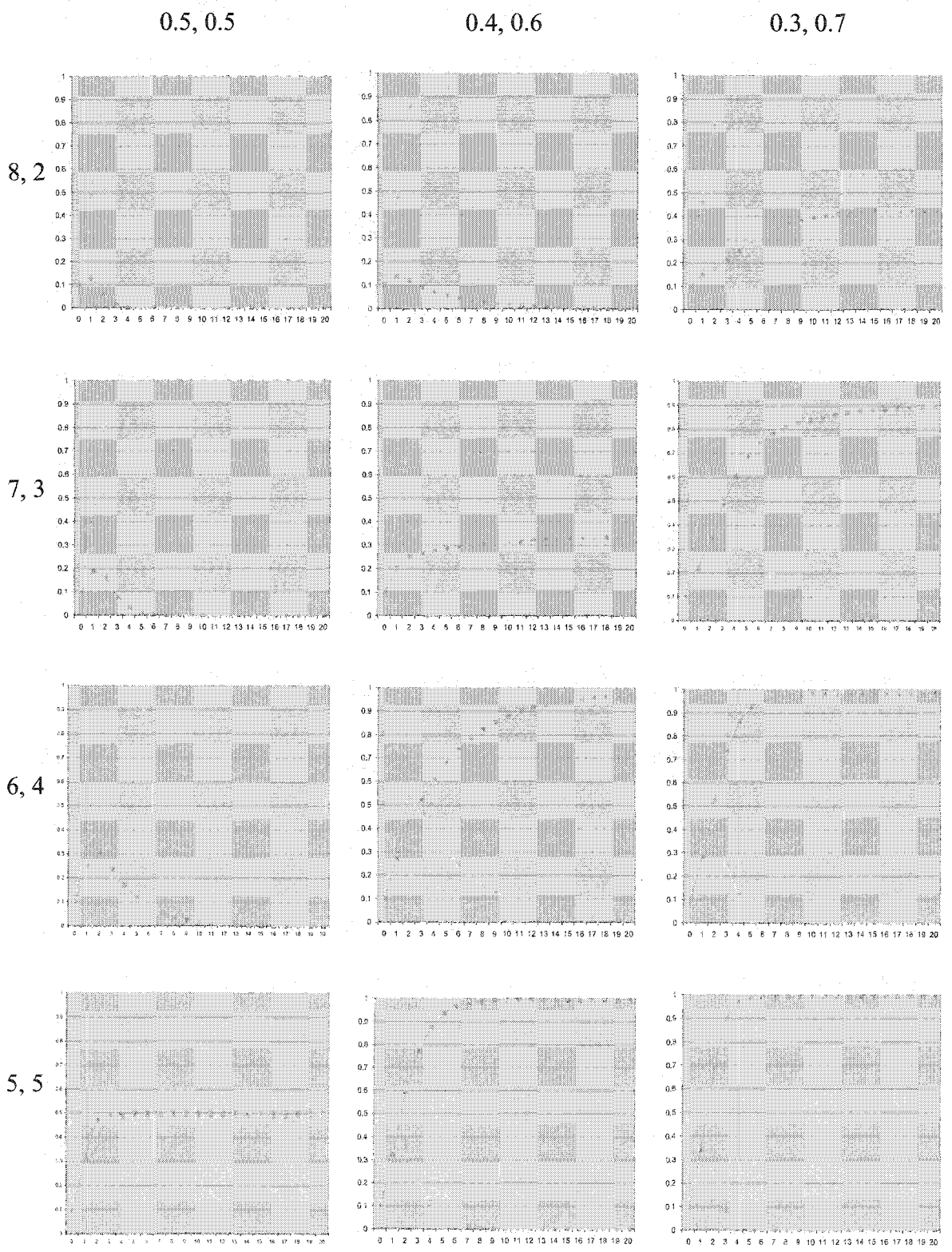

FIGURE 3.11, Results of plant succession model of section 3.3.2, where values of competitiveness are displayed in column headings for species A and species B, respectively, and in the same way values of per-plant fecundity are displayed in row headings.

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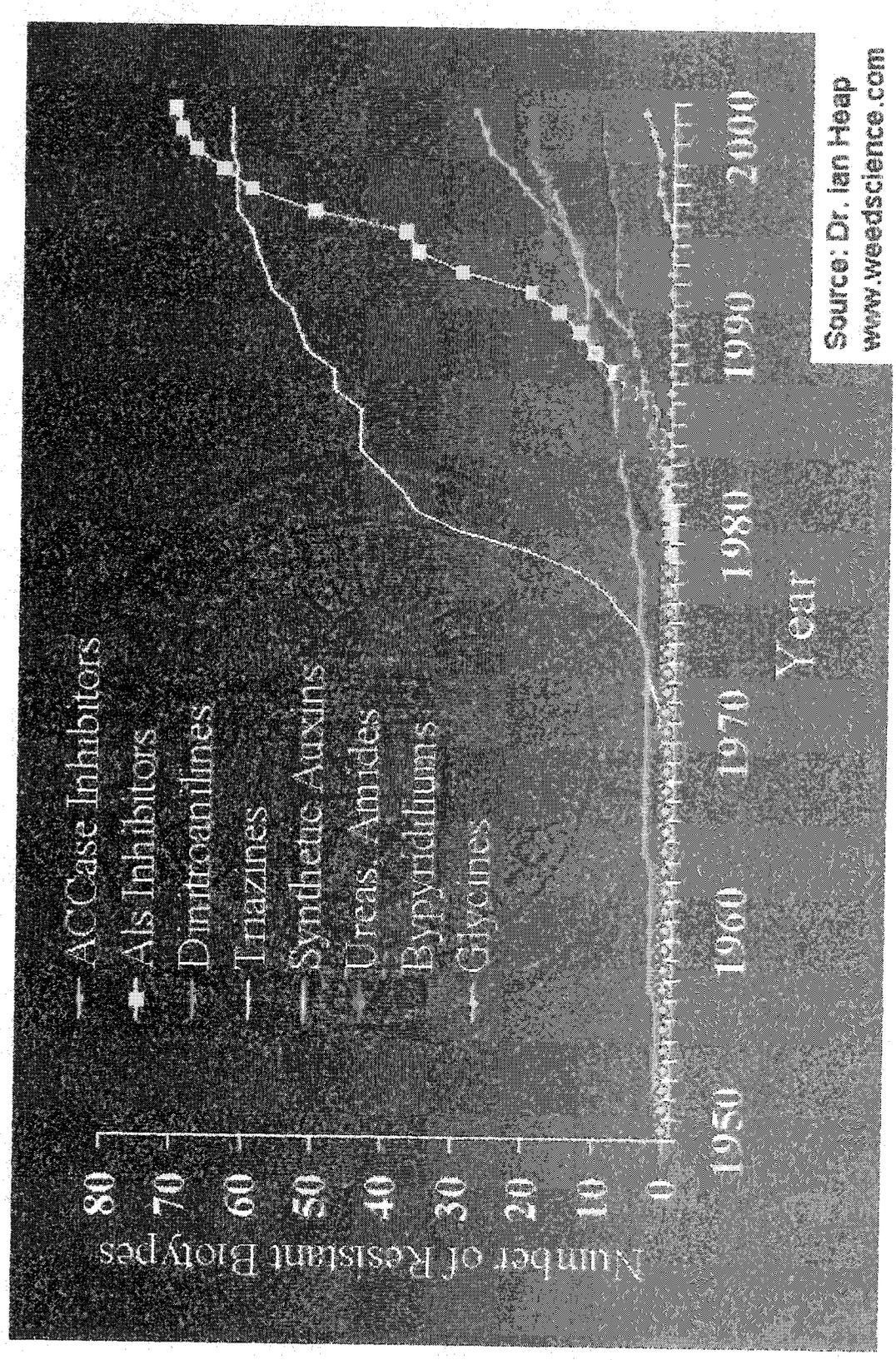

FIGURE 3.12, showing number of tolerant weed biotypes by year for various herbicide modes of action. (Courtesy Dr. Ian Heap, www.weedscience.org).

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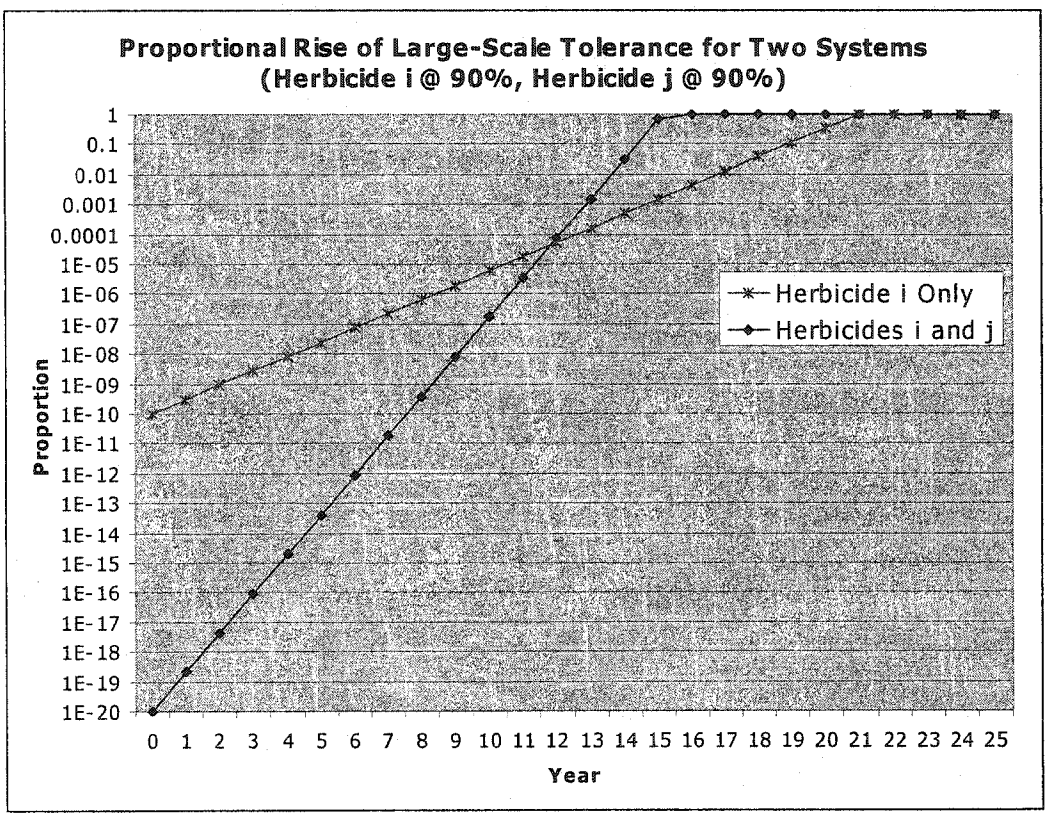

FIGURE 3.13, showing the dynamics of large-scale tolerance for a one and two herbicide system, where both herbicides have efficacies of 90%.

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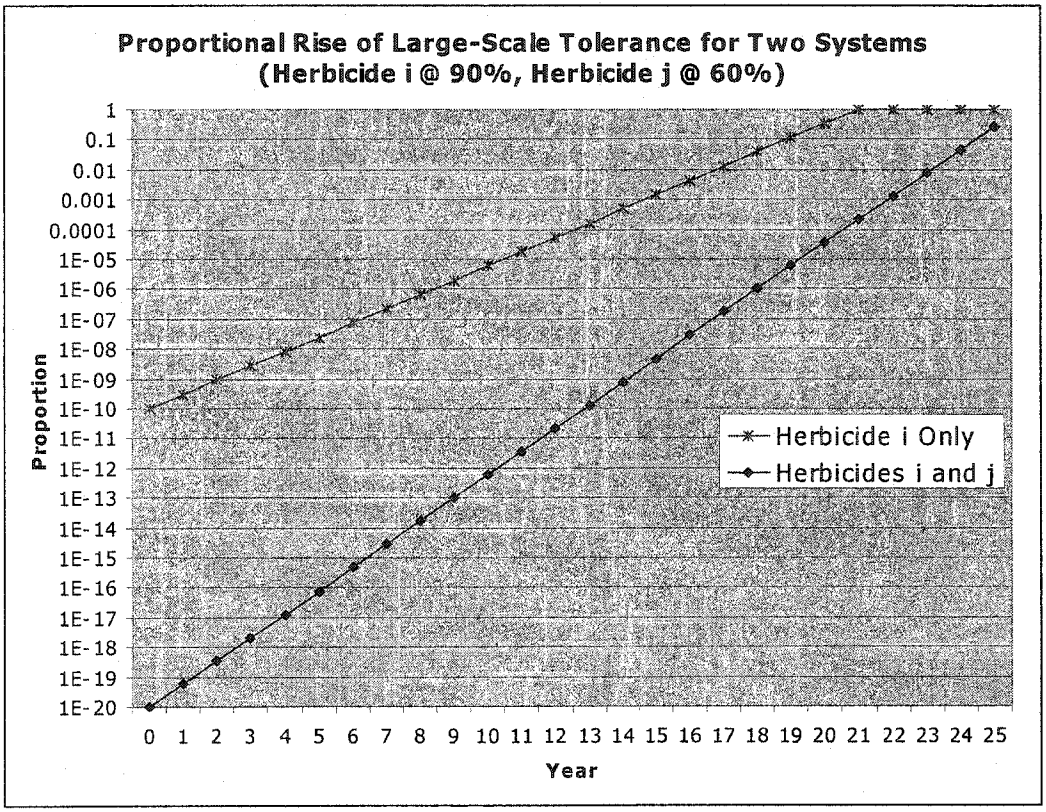

FIGURE 3.14, same as FIGURE 3.13 except that the efficacy of herbicide *j* has been lowered to 60%.

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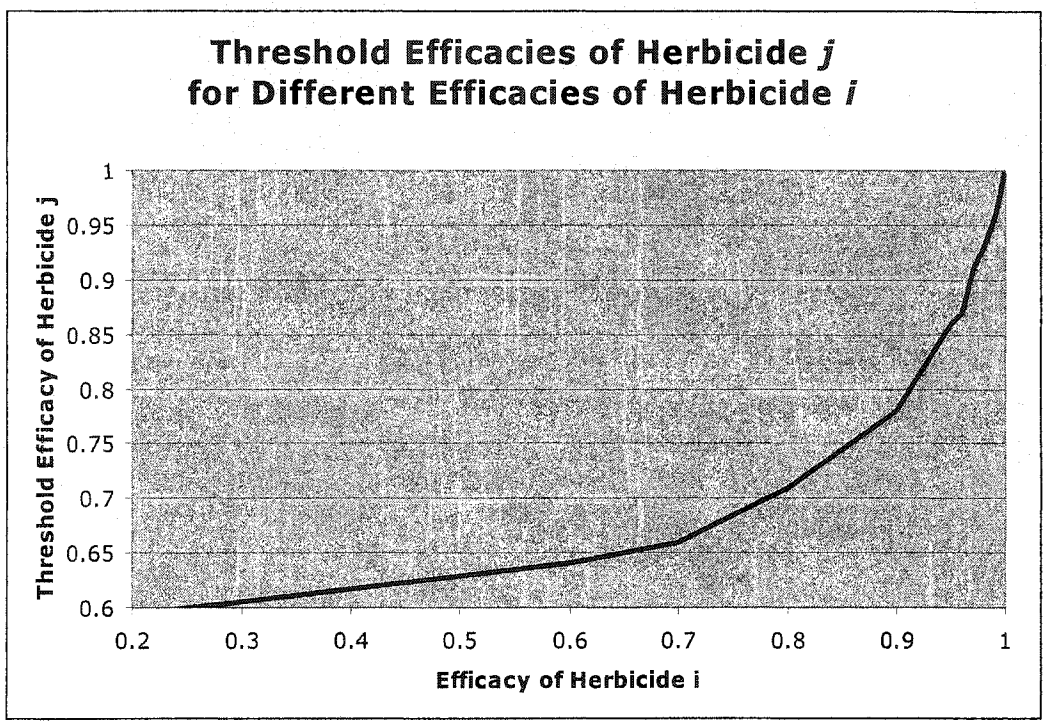

FIGURE 3.15, threshold efficacies of herbicide *j* for different efficacies of herbicide *i*, where seed bank longevity is set to five years, no fitness costs exist, indigenous tolerance proportions are set to 10^{-10}, and tolerant biotypes are completely tolerant ($\tilde{\varepsilon} = 0$).

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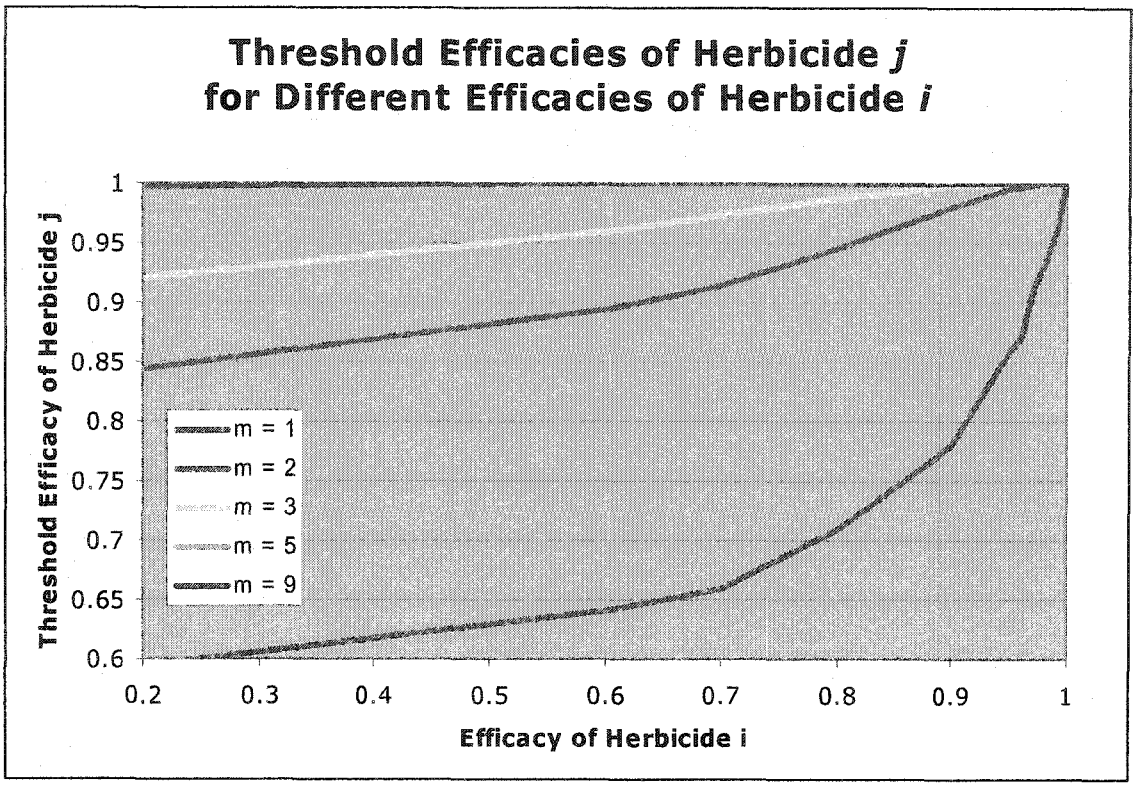

FIGURE 3.16, same as FIGURE 3.15, but with applications of herbicide *j* staggered by a variable number of years (*m*).

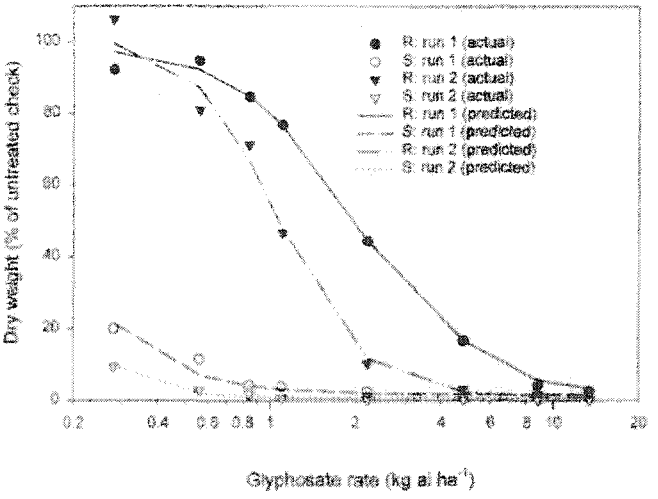

FIGURE 3.17, from VanGessel (2001), showing reductions in dry biomass for different biotypes of horseweed (*Conyza canadensis*) in response to different rates of glyphosate application.

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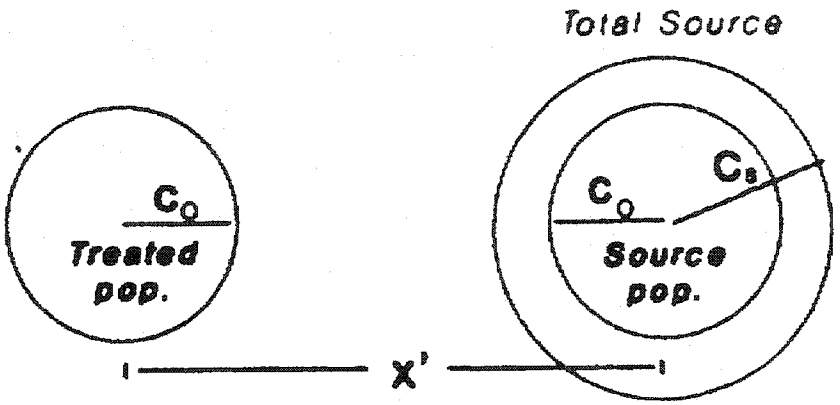

FIGURE 3.18, from Maxwell, Roush, and Radosevich (1990), showing the spatial arrangement of the modeled source and treatment populations.

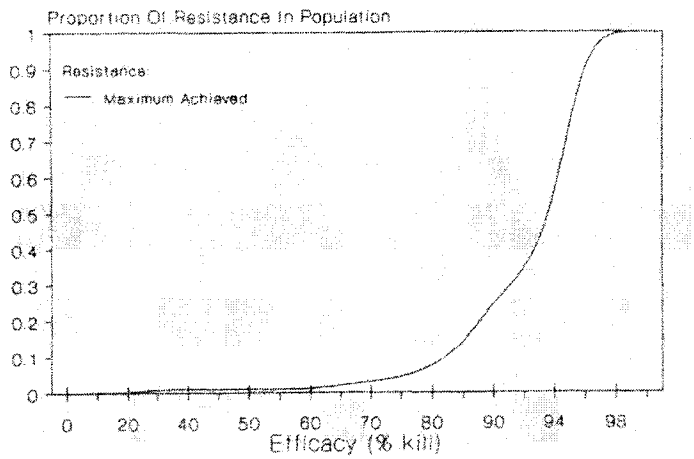

FIGURE 3.19, from Maxwell, Roush, and Radosevich (1990), showing the effect of herbicide efficacy on eventual proportions of herbicide tolerance.

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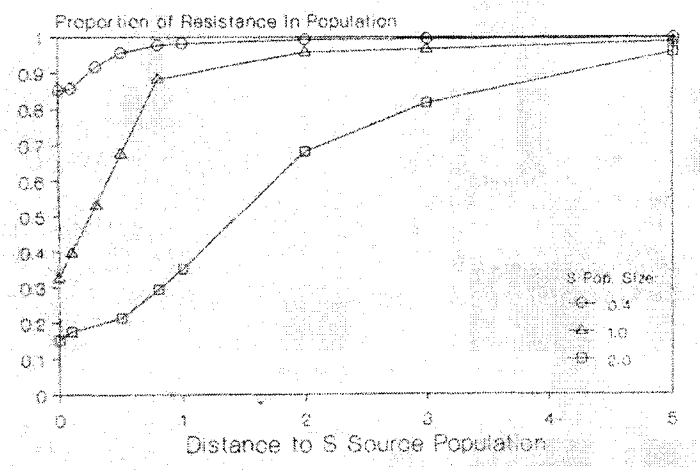

FIGURE 3.20, from Maxwell, Roush, and Radosevich (1990), showing the effect that nearby populations of susceptible biotypes can have on abating the formation of large-scale herbicide tolerance through gene flow.

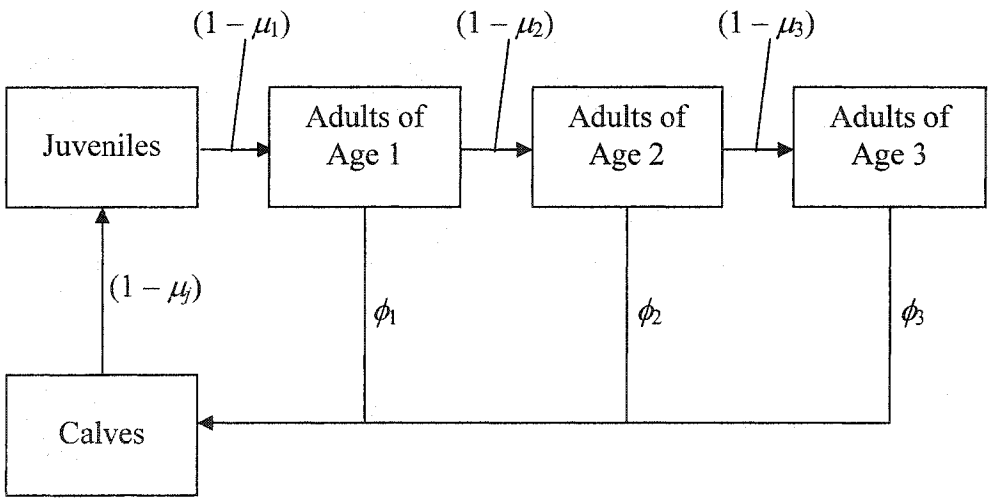

FIGURE 3.21, showing the popular formulation of ecological models with explicit age structure. Here the example is for female mammals, where each value of μ defines an age-specific mortality rate that prevents advancement to the next life stage. In addition, each value of ϕ allows for different levels of fecundity at each life-stage.

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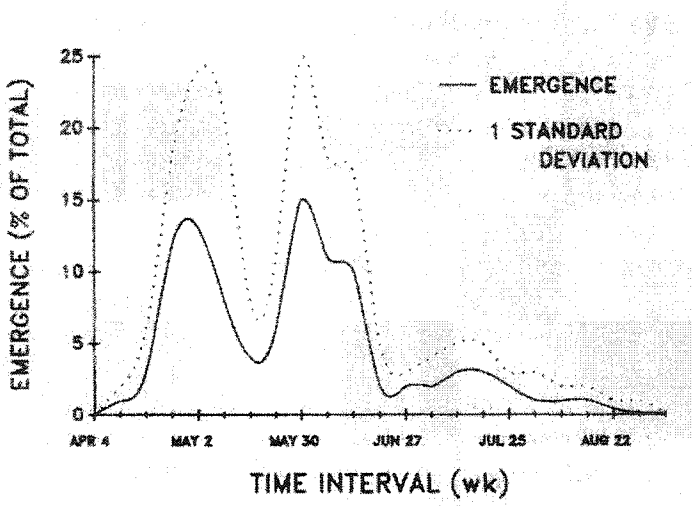

FIGURE 3.22, from Anderson (1994), showing new emergence over the growing season for multiple weed species averaged over seven years.

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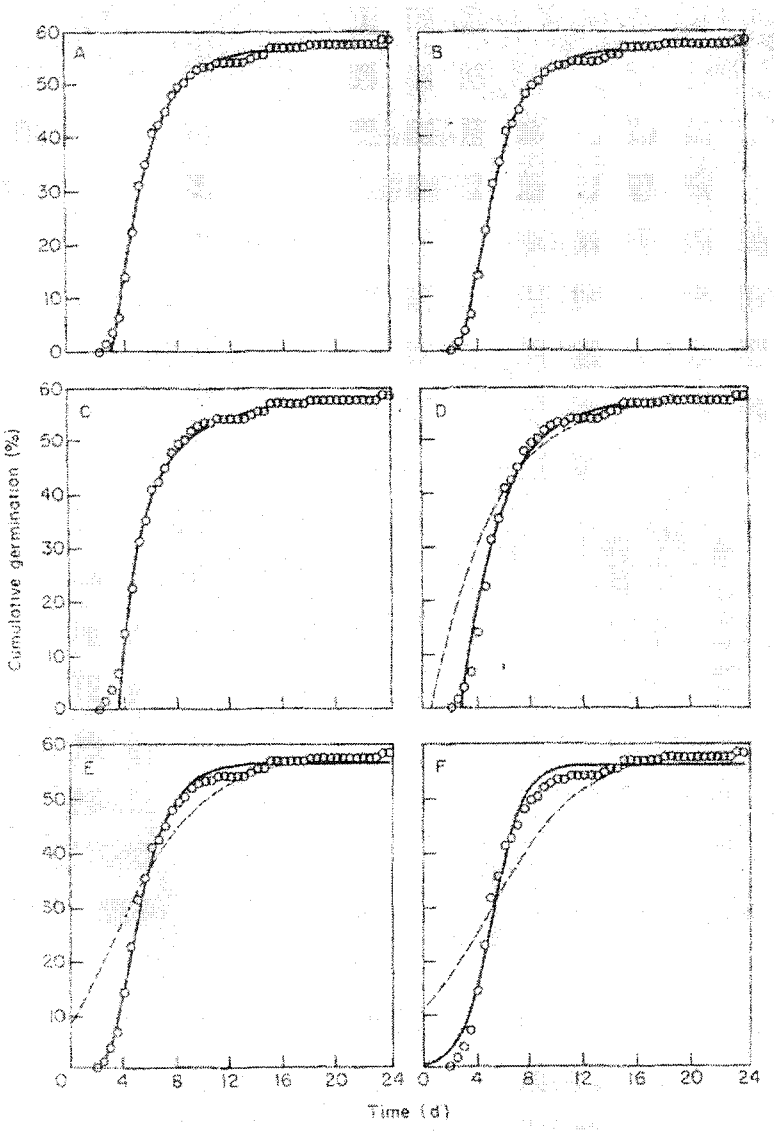

FIGURE 3.23, from Brown and Mayer (1988), showing cumulative germination data (dots) with attempts to fit various models – Weibull (A), Morgan-Mercer-Flodin (B), Richards (C), Mitscherlich (D), Gompertz (E), and logistic (F). Solid lines are curves fitted by non-linear regression. Dashed lines are functions fitted by linear regression.

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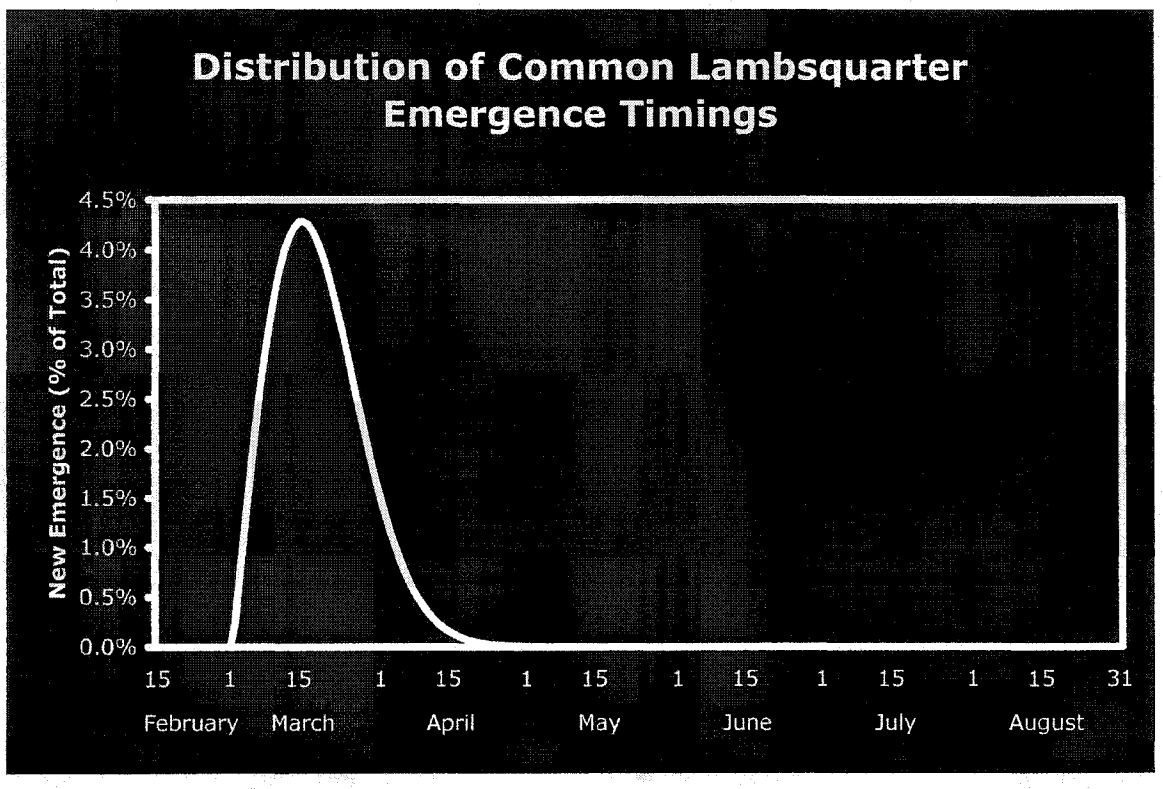

FIGURE 3.24, the continuous Weibull distribution for timing of emergence of common lambsquarters (*Chenopodium album*) in the WISDEM model.

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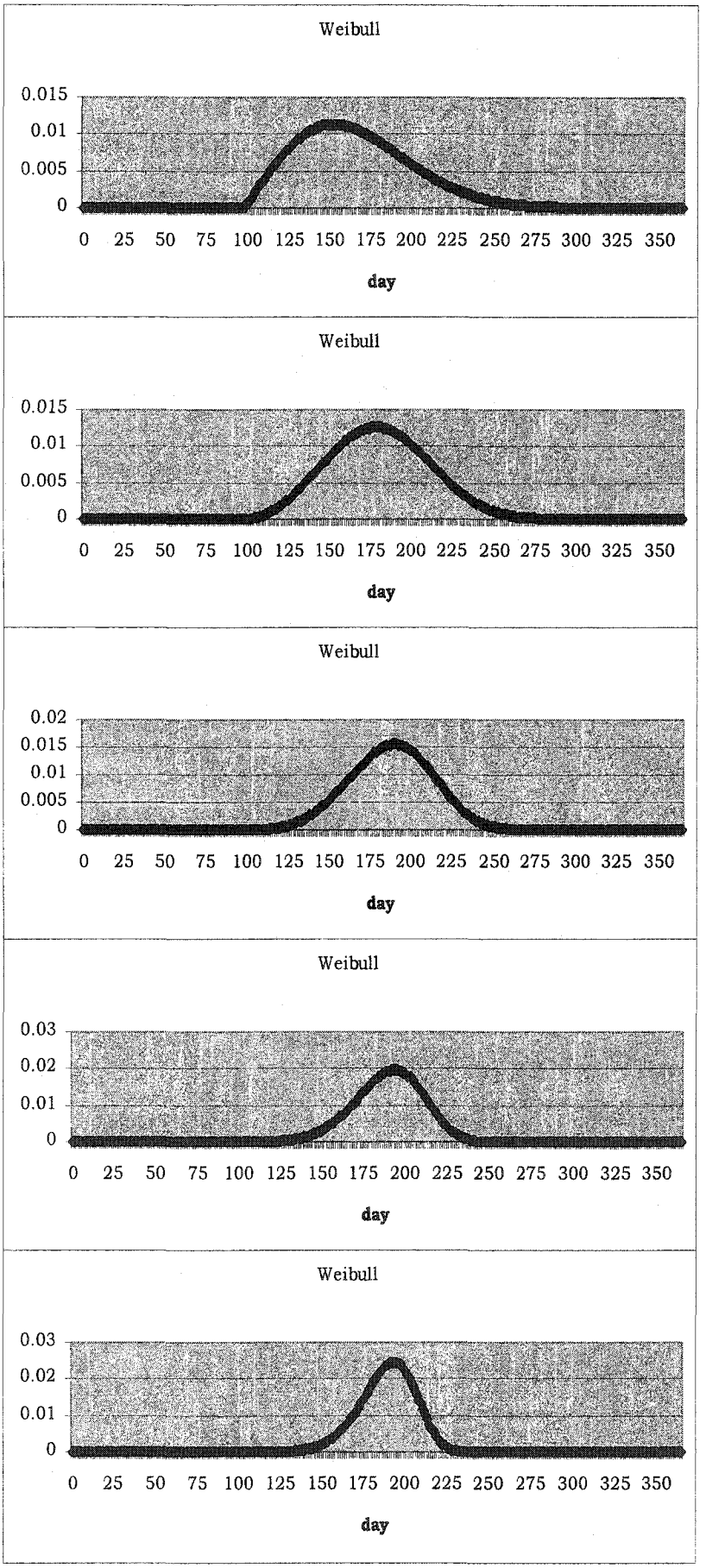

FIGURE 3.25, showing model results for the evolution of an emergence pattern for velvetleaf (*Abutilon theophrasti*). Results are for successive seasons and Julian dates are displayed across the *x*-axis. The shift is caused by an herbicide application on April 30th of each year that has an efficacy of 90%.

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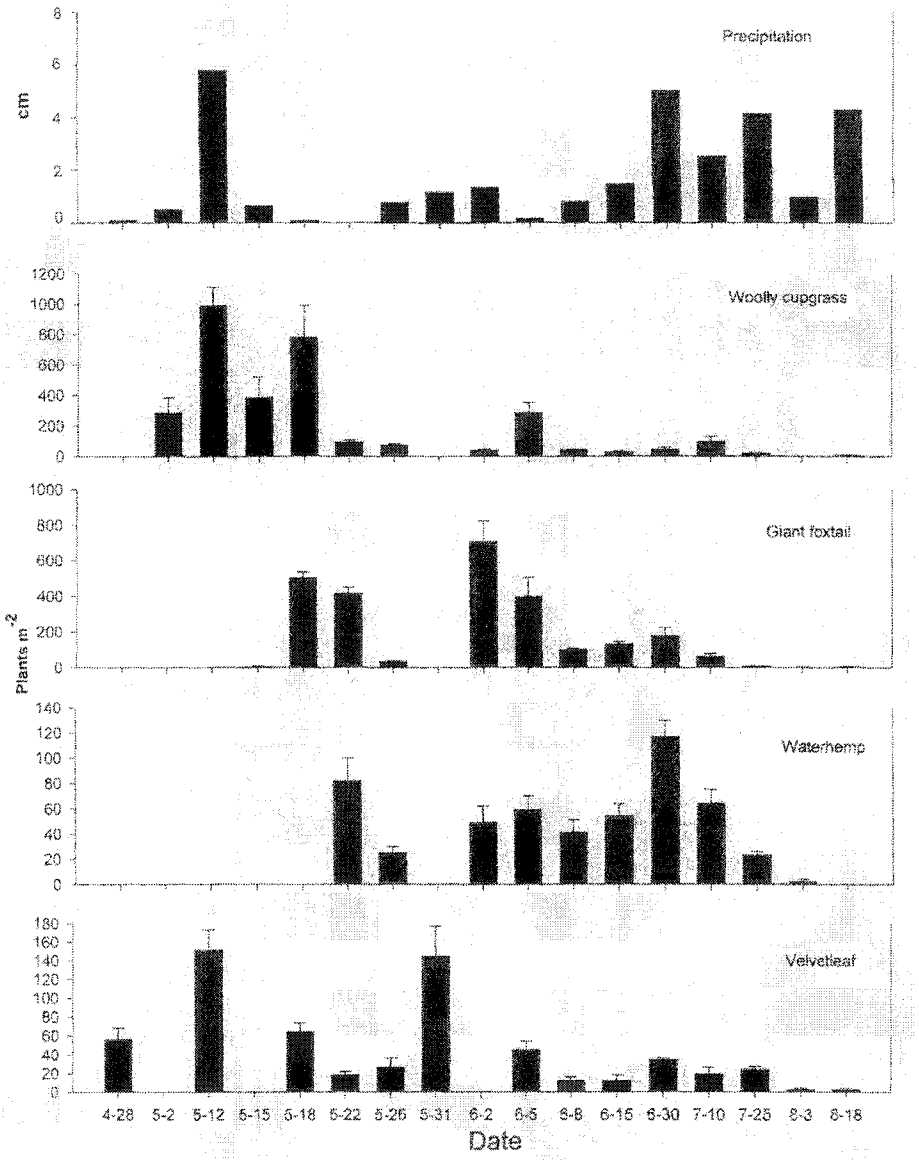

FIGURE 3.26, from Hartzler et al. (1999), showing precipitation data with emergence patterns of wooly cupgrass (*Eriochloa villosa*), giant foxtail (*Setaria faberi*), waterhemp (*Amaranthus rudis*) and velvetleaf (*Abutilon theophrasti*) for the 1995 season.

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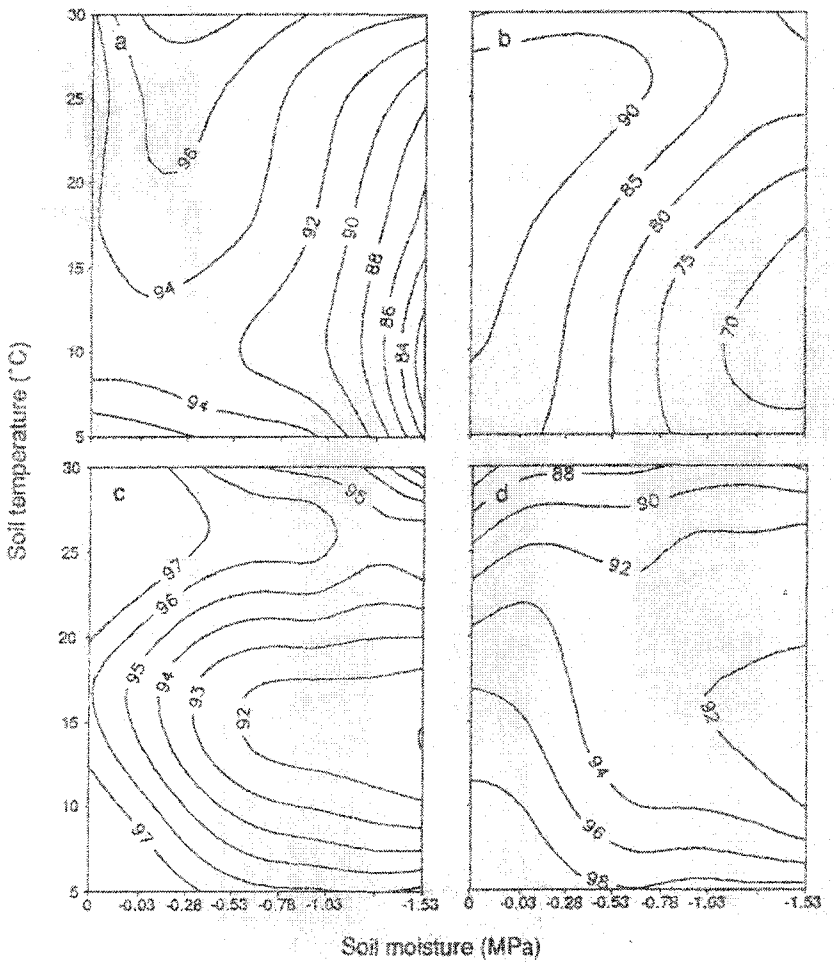

FIGURE 3.27, from Blackshaw (1991), showing the effects of soil temperature and moisture on the percentage emergence of (a) downy brome, (b) winter canola, (c) winter wheat, and (d) winter rye under controlled environmental conditions.

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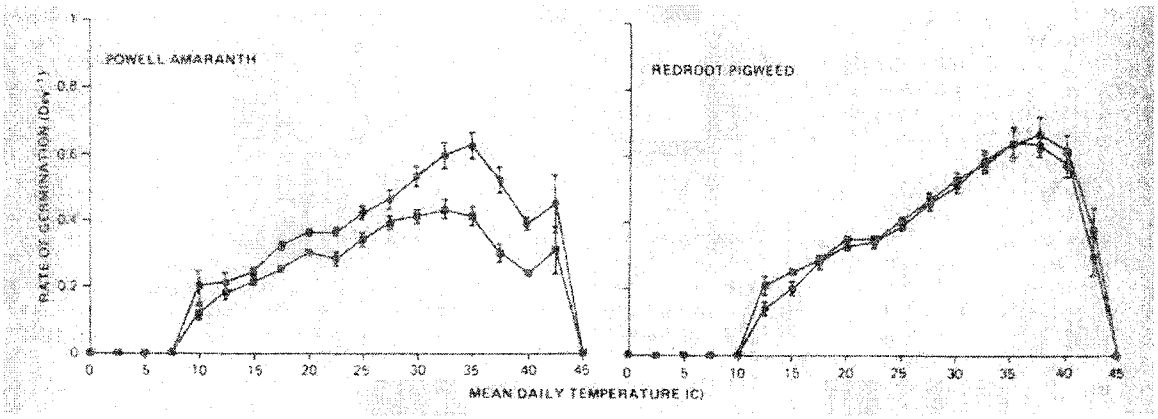

FIGURE 3.28, from Weaver and Thomas (1986), showing germination rates for two biotypes of powell amaranth and redroot pigweed over different temperatures. For each species the biotypes are an atrazine-tolerant and an atrazine-susceptible biotype (squares and dots, respectively.

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Chapter 4.0
Literature Review III: Three Major Challenges

"I will take the ring to Mordor, though I do not know the way."
J. R. R. Tolkien

The last portion of any literature review involves a kind of deductive meta-analysis, whereby large-scale questions and areas of necessary future study are elucidated and described in detail. In this chapter such is performed for the present subject matter, and it is stated in the form of three challenges that will need to be overcome if weed simulation modeling techniques are to become more widely utilized and accepted. The chapter ends with a section that gives a present-day roll call and lineage for the most major weed simulation models of our time.

4.1 Environmental Effects: The Challenges of Multi-Regional Modeling

One of the largely untested aspects of simulating weed populations involves the applicability of competition relationships derived from experiments in a given location to populations in other geographic locations. Implicit in this question is the role of environmental dynamics in the variation of competition and other demographic parameters. Jasieniuk et al. (1999) investigated the variation in these parameters for interference relationships of winter wheat (*Triticum aestivum*) and jointed goatgrass

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(*Aegilops cylindrica*) in multiple locations and multiple seasons. It was found that variation was more significant from one location to the next than from one season to the next. Referring to the parameters of the model of Cousens (1985), it was found that variation in the I parameter was more associated with site-to-site changes, whereas variation in the A parameter was more associated with season-to-season changes. Swinton et al. (1994) examined year-to-year parameter variation with a multiple-species version of equation [2.3], and found sufficient evidence for season-specific variation of the weed-free yield parameter (Y_{wf}), but found the other competition coefficients to be relatively stable.

A similar analysis can be performed on interference relationships between corn (*Zea mays*) and giant foxtail (*Setaria faberi*) by pooling together the data from two studies. The results of Fausey et al. (1997) are shown in TABLE 4.1, where standard errors are displayed in parentheses. In addition, Lindquist et al. (1999) studied interference relationships between the same species, arriving at the parameter values shown in TABLE 4.2 for a variety of locations. This combined dataset is plotted in FIGURES 4.1 and 4.2 along with standard errors for each parameter. Although certain regions of preponderance are clearly visible, significant variation is also apparent.

In addition to purely random experimental error, such variation may be the result of variances in a wide range of factors such as:

a. Crop seeding density

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b. Relative time of emergence of crop and weed

c. Environmental differences

d. Differences in soil type

e. Spatially dependent factors related to variances in weed aggregation

The fact that the error bars on individual studies are rather large suggests very strongly the importance of the latter two factors. Little means exists at this time for exploring these aspects much further. The first three, however, can be explored to some extent.

TABLE 4.3 shows information from the latter study concerning planting dates and crop seeding rates. In FIGURES 4.3 and 4.4 the parameters I and A are respectively plotted against differences in crop seeding density. Dependencies are inconclusive. Relative time of emergence may be indirectly addressed in the FIGURES 4.5 and 4.6 by relating parameter values to crop planting date. Inasmuch as dependencies appear to be more visible, this result may indirectly confirm the findings of multiple previous authors who have cited relative time of emergence as a factor whose importance in crop yield loss rivals even the importance of weed density (e.g., Dieleman et al., 1995; Knezevic et al., 1994). As was discussed in chapter 2, Cousens et al. (1987) modeled this dependence by adding an additional parameter to the previous equation of Cousens (1985):

$$Y = Y_{wf}\left(1 - \frac{IN_1}{e^{c(t_w - t_c)} + IN_1/A}\right)$$

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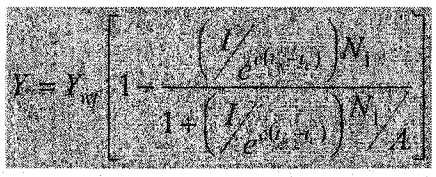
where t_w and t_c are the dates of weed and crop emergence, respectively. If the two emerge simultaneously, this first term in the denominator becomes a 1, and if the following algebra is performed:



[4.1]

then it is suggested that variances in relative emergence time will be associated more directly with changes in I, but not A. Such is not generally supported by FIGURES 4.5 and 4.6, where some dependencies of both on emergence appear to be visible. The regression statistics, however, do not conclusively support either such dependence.

Aspects of environmental differences were addressed by performing additional regression analyses on monthly average mean temperatures and monthly precipitation totals for each of the locations in the above studies. In particular the monthly average mean temperatures provide insights into rates of growth and metabolism since, as is shown in Appendix B, they are related to degree days. Since only 8 data points existed for this investigation, models involving more than two independent variables were not considered in the selection process. The top two models in the selection process are shown in TABLE 4.4. In both cases all non-intercept model parameters are significant under $\alpha = 0.05$. Although Model 2 has a higher R^2 value, Model 1 has a higher adjusted R^2 value and a lower AICC value. For both models an investigation into model residuals showed no apparent violations of the assumptions of linear regression. Thus, model 1

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was chosen as the best model. Some insight into a possible causal relationship may be attainable from the fact that corn development is sensitive to precipitation in July (D'Amato, personal communication). FIGURE 4.7 shows these I values plotted with predicted values from Model 1 on a regression line plotted against July precipitation, where July precipitation is shown in inches.

Similar analyses were also made on the A parameter employing the same methodology and constraints, resulting in the two top models shown in TABLE 4.5, where C_p indicates Mallow's C_p. Again, in both cases all non-intercept parameters were significant at $\alpha = 0.05$, and an inspection of the residuals showed no overt violations of regression assumptions. In this case no clear distinction can be made between the two models, and so Model 1 is chosen since it involves fewer parameters. FIGURE 4.8 shows these A values plotted with predicted values from Model 1 on a regression line plotted against average mean August temperatures, where temperatures are displayed in degrees Fahrenheit.

In reference to section 3.1 from the previous chapter, a fitting of the above data to the following equations:

$$\frac{N_c}{Y} = \beta_0 + \beta_{cc}N_c + \beta_{cw}N_w \qquad \frac{N_c}{Y} = \beta_0 + \beta_{cc}N_c + \beta_{cw}N_w + \beta_{ccw}N_cN_w$$

was also desired, and was attempted in a preliminary fashion using a recreation of the predicted values of Y for values of N_w in the following set:

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$$N_w \in \{0.1, 0.2, 0.3, \ldots, 20.0\}$$

Thus, this study is really a fitting to the predicted values from each of the above studies:

$$\frac{N_c}{\hat{Y}} = \beta_0 + \beta_{fc} N_c + \beta_{cw} N_w \qquad [4.2]$$

$$\frac{N_c}{\hat{Y}} = \beta_0 + \beta_{fc} N_c + \beta_{cw} N_w + \beta_{fcw} N_c N_w \qquad [4.3]$$

where $\hat{Y}$ denotes predicted values of yield from the studies. The results are displayed in TABLE 4.6 for the first model and in TABLE 4.7 for the second model. Although it is to be acknowledged that the p values shown in these ANOVA tables are of compromised significance, they still potentially provide an initial indication of the viability of the above models. However, with R^2 values of 43.5 and 43.7% respectively, additional dependencies of the above parameters on similar environmental factors was also considered.

To do this, however, one must address the character of how the β coefficients in the following models:

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$$\frac{N_c}{\hat{Y}} = \beta_0 + \beta_{cc}N_c + \beta_{cw}N_w \qquad \frac{N_c}{\hat{Y}} = \beta_0 + \beta_{cc}N_c + \beta_{cw}N_w + \beta_{ccw}N_cN_w$$

will respond to environmental changes given that A and I coefficients in the following model of the same data:

$$Y = Y_{wf}\left(1 - \frac{IN_w}{1 + IN_w/A}\right)$$

display linear relationships with August average temperatures and July precipitation, respectively. Adjusting the above equation we have:

$$\frac{N_c}{Y} = \frac{N_c}{Y_{wf}}\left(\frac{1}{1 - \frac{IN_w}{1 + IN_w/A}}\right) = \frac{N_c}{Y_{wf}}\left[1 + \frac{AIN_w}{A + (1-A)IN_w}\right]$$

In an effort to linearize the above equation we approximate the denominator with average parameter values:

$$\frac{N_c}{Y} \approx \frac{N_c}{Y_{wf}}\left[1 + \frac{AIN_w}{A + (1-\bar{A})\bar{I}N_w}\right] = \left[\frac{1}{Y_{wf}}\right]N_c + \left[\frac{1}{Y_{wf}}\frac{AI}{A + (1-\bar{A})\bar{I}N_w}\right]N_cN_w$$

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which implies a vulnerability of the interaction term towards a dependence with the above environmental factors. Such is tested with the ANOVA table in TABLE 4.8. Linear dependencies on N_c and N_w were also investigated, and, for N_c, rejected. In particular notice in TABLE 4.8 that the R^2 value has risen to 88.8%.

Thus, the following equation:

$$\frac{N_w}{Y} = 1.1956 + 1.285N_c + (11.2215 - 0.4159P_{prior} + 0.1249T_{prior})N_w + (-1.3019 + 0.069P_{prior} + 0.0131T_{prior})N_c N_w \quad [4.4]$$

may provide significant potential predictive power regarding the interaction between corn and *Setaria faberi*, and should be tested in subsequent studies thus.

From a general perspective, the above study implies strong environmental influences on plant competition parameters. In reference to sections 2.3 and 3.7, it appears reasonable to hypothesize that these environmental influences interact with weed competition dynamics through enacting variances in relative emergence timing. Jasieniuk et al. (1999) echo this observation by hypothesizing that predictive ability of their competition models would have been significantly improved with an incorporation of relative time of emergence into the model.

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4.2 Gathering Data and Minimizing Complexity: The Challenges of Multi-Species Modeling

Modeling projects rely profoundly on the rather heroic experimental efforts of weed scientists and ecologists, who routinely involve themselves in the painstaking processes of gathering samples of weed population and soil seed bank population data in various field studies under environmental conditions that are sometimes far from comfortable.

As a result it is understandable that the resulting parameters of survival, emergence, competition, and seed production do not exist for every combination of plant species encountered in agronomic scenarios. As will be observed in chapter 7, the process of incorporating parameter values for additional species into a model oftentimes requires some degree of indirect deduction.

Obviously, the more data one has, usually the more powerful is the model. However, from a model creation perspective this section speaks to two elements of importance:

1. The model algorithm must be restricted to the most significant key processes. This involves a solid quantitative theoretical framework of what elements produce the most predictive power as well as at what point the inclusion

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of additional processes or state variables results in a kind of diminishing return in predictive power.

In the case of the model introduced in chapter 7 the key processes that are included are as follows:

a. Seed Bank Mortality

b. Emergence Proportion

c. Timing of Emergence

d. Competition Parameters

e. Herbicide, Tillage, and Harvest Efficacies

f. Seed Rain Production

All of the above represent processes of demonstrated importance, but what is also significant here are the processes and elements of variation that are excluded, such as effects of soil organic matter, vertical seed bank distributions, and effects of herbicides on plant fecundity. Again, it is not disputed that such processes can have significant effects in some situations, but for the purposes of simulating weed shifts in Roundup Ready™ crops it is hypothesized that much of the variation in weed populations can be explained without including such processes.

2. The included model processes must be represented in a fashion that is as simplistic and easily-obtainable as possible. Controlling for differences in

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emergence timing, competition parameters are assumed to be constant, and herbicides and control processes are represented as simple percentage losses to plant populations and, thus, seed production.

In addition, although seed bank mortality, emergence proportion, and seed rain production are included in the model, they do not have to be explicitly measured in the field. In the model to follow they are implicitly represented as maximum and minimum population growth rates under conditions of no control or complete control, elements that are far easier to obtain from field studies and can even be obtained from expert opinion (Dunan et al. 1999). For the model to follow this must not be credited to the present author, but the model's former lineage (Wiles et al., 1996; Canner, Wiles, and McMaster, 2002).

With the above in mind, it is believed that the results of such competition studies described can be used in a fashion that optimizes their functionality and significantly honors the efforts of those whose work has made the model creation possible.

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4.3 Prediction Error: The Challenges of Long-Term Modeling

4.3.1 Prediction Error and Its Sources

As was mentioned in section 2.4.5, in evaluating the relative desirability of two candidate herbicide treatments, for example, a grower may wish to be aware of the uncertainties associated with each of the treatment's calculated cost-effectiveness. To some extent a grower will already possess some understanding of this implicit uncertainty, which would, for example, cause an herbicide treatment calculated to result in a net profit of only 50 cents per acre to be viewed with some skepticism as to its viability as a risk. There is, however, more that can be provided.

Ideally this understanding of prediction error would result in a distribution of possible model results much like what is discussed in section 2.4.5, and would result from known uncertainties in the following three categories:

1. Uncertainties in the model parameters,
2. Uncertainties in values of initial state variables, and
3. Inabilities of the model to explain all variance in predicted values.
4. Predictive limitations of a chaotic system.

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Implicit in the above discussion is the desire to know at what point predictions of populations contain errors that are large enough to make the predictions invalid. This may be of some significance in the present modeling project since it has been stated that in the dynamics of multiple-species plant competition, chaotic phenomena should most likely be the rule instead of the exception (Pahl-Wostl, 1995). When a given set of uncertainties is known, such calculations can be achieved through a Monte Carlo technique. However, in any modeling approach it is first appropriate to assess the degree to which insight can be gained through analytical means. In this discussion the following notation is used to denote, respectively, the expectation, the variance, and the standard error of a given random variable:

$$E\{X\} = \mu_X \qquad \sigma^2\{X\} \qquad se\{X\}$$

where X is a random variable, and the following relation is known:

$$se\{X\} = \sqrt{\sigma^2\{X\}}$$

In an analysis of the growth of prediction error we seek to understand the evolution of a quantity defined here as 'fractional' standard error:

$$\frac{se\{X\}}{X}$$

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where a value of the above quantity that is close to one would indicate a prediction that is unreliable, and, specifically in regards to weed populations, the following random variable η describes the growth rate of this fractional standard error:

$$\eta = \frac{\frac{se\{N_{t+1}\}}{N_{t+1}}}{\frac{se\{N_t\}}{N_t}} \qquad [4.5]$$

where η is a random variable since it is equal to the quotient of a parameter and a random variable, and a value of η that is greater than one indicates an annual growth rate of this fractional standard error. The following section shows a "simple" example in which values of this random variable are investigated.

4.3.2 The Exponential Model

We begin with the simplest model:

$$N_{t+1} = \lambda N_t$$

where λ denotes an annual growth rate that is exponential in nature. If one begins with initial values of weed density that are known to contain some uncertainty (uncertainty type 2 from the previous subsection), then its initial fractional standard error is as follows:

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$$\frac{se\{N_0\}}{N_0}$$

and the growth of this fractional standard error would proceed as follows:

$$\eta = \frac{se\{N_{t+1}\}/N_{t+1}}{se\{N_t\}/N_t} = \frac{\sqrt{\sigma^2\{\lambda N_t\}}/\lambda N_t}{\sqrt{\sigma^2\{N_t\}}/N_t} = \frac{1}{\lambda}\frac{\sqrt{\sigma^2\{\lambda N_t\}}}{\sqrt{\sigma^2\{N_t\}}}$$

Interestingly enough, if this is the only one of the four sources of error that is present, then this growth rate reduces to:

$$\eta = \frac{1}{\lambda}\frac{\sqrt{\sigma^2\{\lambda N_t\}}}{\sqrt{\sigma^2\{N_t\}}} = \frac{1}{\lambda}\frac{\sqrt{\lambda^2\sigma^2\{N_t\}}}{\sqrt{\sigma^2\{N_t\}}} = 1 \qquad [4.6]$$

which indicates that in the absence of uncertainties in the model parameters and limitations in the model's ability to explain variance, then no increases occur in the fractional standard error over time, a fact that is somewhat encouraging in the field of weed science, since in such contexts weed population dynamics tend to follow patterns of exponential growth and decline.

However, with the inclusion of uncertainty type 3 from the previous subsection, the exponential equation becomes:

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$$N_{t+1} = \lambda N_t + \varepsilon$$

where an error term is attached to openly embrace the model's inability to explain all aspects of variance. This error term, ε, is assumed to be a random variable completely uncorrelated with N_t.

As a result, equation [4.6] becomes:

$$\eta = \frac{1}{\lambda}\frac{\sqrt{\sigma^2\{\lambda N_t + \varepsilon\}}}{\sqrt{\sigma^2\{N_t\}}} = \frac{1}{\lambda}\frac{\sqrt{\lambda^2\sigma^2\{N_t\} + \sigma^2\{\varepsilon\}}}{\sqrt{\sigma^2\{N_t\}}} = 1 + \frac{1}{\lambda}\frac{\sqrt{\sigma^2\{\varepsilon\}}}{\sqrt{\sigma^2\{N_t\}}} = 1 + \frac{1}{\lambda}\frac{\sigma_\varepsilon}{se\{N_t\}} \quad [4.7]$$

where the following relationship has been utilized:

$$\sigma^2\{A \pm B\} = \sigma^2\{A\} + \sigma^2\{B\} + 2\sigma\{A, B\}$$

along with the assumption that N_t and ε are uncorrelated. Here it is now visible that, since all elements in the latter term are positive, an increasing fractional standard error is now observed. Here σ_ε denotes the square root of the variance associated with the type 3 uncertainty.

The allowance of uncertainty in the model parameter λ now makes the expression more complex:

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$$\eta = \frac{1}{\lambda}\frac{\sqrt{\sigma^2\{\lambda N_t + \varepsilon\}}}{\sqrt{\sigma^2\{N_t\}}} = \frac{1}{\lambda}\frac{\sqrt{\sigma^2\{\lambda N_t\} + \sigma_\varepsilon^2}}{\sqrt{\sigma^2\{N_t\}}}$$

where σ_ε^2 is the variance associated with the type 3 uncertainty. The variance of the product of λ and N_t has a complex expansion that can be derived from the Law of Total Variance (Theorem 14 from Lindgren, 1993):

$$\sigma^2\{\lambda N_t\} = \sigma_\lambda^2\mu_{N_t}^2 + \sigma_{N_t}^2\left[\mu_\lambda^2 + \sigma_\lambda^2\right]$$

where the expected value and variance of a given variable or parameter are denoted respectively with the variables μ and σ^2 having the featured variable or parameter as a subscript, and the assumption has been made that λ and N_t are independent of each other. The expression for η becomes:

$$\eta = \frac{\sqrt{\sigma_\lambda^2\mu_{N_t}^2 + \sigma_{N_t}^2\left[\mu_\lambda^2 + \sigma_\lambda^2\right] + \sigma_\varepsilon^2}\Big/\lambda N_t}{\sqrt{\sigma_{N_t}^2}\Big/N_t} = \frac{1}{\lambda}\sqrt{\mu_\lambda^2 + \sigma_\lambda^2 + \frac{\sigma_\varepsilon^2}{\sigma_{N_t}^2} + \mu_{N_t}^2\frac{\sigma_\lambda^2}{\sigma_{N_t}^2}}$$

and if the assumption is made that variations on λ are minor:

$$\lambda \approx \mu_\lambda$$

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then the expression for η becomes:

$$\eta \approx \sqrt{1 + \frac{\sigma_z^2}{\mu_z^2} + \frac{\sigma_z^2}{\mu_z^2 \sigma_N^2} + \frac{\mu_N^2}{\mu_z^2} \frac{\sigma_z^2}{\sigma_N^2}} \qquad [4.8]$$

where it is immediately visible that η is always greater than 1, and the three latter terms under the radical respectively denote the square of the relative standard error of the growth rate, an interaction term that appears to allow for a rapid increase (high η) in instances where the initial relative standard error of the population is very low (relative to the relative standard error of the growth rate) and vice versa, and lastly a term to govern the increase in relative standard error in response to type 3 uncertainty.

Unfortunately, assessments of prediction error for most models involving more explicit representations of plant process will almost certainly require non-analytical means such as a Monte Carlo technique. Any analytical investigation would at the very least require assumptions regarding correlations among uncertainties in the model parameters and would most likely result in expressions far more complex than those described in this section. However, the above mathematical exercises do illustrate how multiple sources of error can display an additive nature as well as the fact that only certain forms of uncertainty may interact with each other.

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4.4 The Major Models

Three major movements in weed modeling have taken place since the early 1990's to create decision-aid tools that begin to transcend at least one of the issues described in the previous three sections of this chapter. Each of them have developed histories of usage and, in some cases, revision. For this reason they are each described as model "lineages", and such histories are described in this section.

4.4.1 North Carolina: The HERB Model Lineage

The HERB model appears to be most closely associated with G. G. Wilkerson and H. D. Coble from North Carolina State University. Its first appearance was with Wilkerson et al. (1991) where it was announced as a decision-aid tool for choosing optimal herbicides (thus, the name). It represented the advent of the following summation of weed densities from multiple species, each weighted by a "competitive index":

$$\sum_{i=1}^{n} \kappa_i N_i$$

as a way of gauging the total competitive effect of all weed species. In relation to the above quantity yield loss was taken to be linear with low weed densities and hyperbolic with higher weed densities:

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$$y_L = \begin{cases} 0.005\sum_{i=1}^{n} \kappa_i N_i & \sum_{i=1}^{n} \kappa_i N_i \le 50 \\ \dfrac{\sum_{i=1}^{n} \kappa_i N_i - 50}{0.25 + 0.55\dfrac{\sum_{i=1}^{n} \kappa_i N_i - 50}{60 + \sum_{i=1}^{n} \kappa_i N_i}} & \sum_{i=1}^{n} \kappa_i N_i > 50 \end{cases} \qquad [4.9]$$

where the effects of herbicide *j* were calculated for each weed species *i*:

$$N_i = (1 - \varepsilon_{ij}) N_i$$

and net return for each herbicide was calculated using equation [2.8]. What is noteworthy is that herbicide efficacy was also made to be dependent on weed size and soil moisture, where in both cases three categories were given for easy reporting (see item 2 in section 4.2). Specifically it was introduced as a successful decision-aid for weed control in soybean. White and Coble (1997) successfully validated HERB for use in peanut crops (*Arachis hypogaea*). This involved calculating new competitive indices for all weeds as well as updating equation [4.9] to be exclusively hyperbolic. Shaw et al. (1998) tested HERB along with a similar model from Arkansas (SWC) on seven soybean trials in Mississippi. Decisions made from the above two models were also compared with decisions made from various experts. What was interesting is that HERB and SWC were reported to agree on their recommendations only 14% of the time, but insight into this appears to be gained from the fact that even the experts agreed on their

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recommendations only 33% of the time. Instances of poor model performance were attributed to complex weed emergence timings and varied production practices.

HERB was one of two models to be the first to model the effects of herbicides among multiple weed species (section 4.2) and represented the first bioeconomic model to be tested in multiple geographic locations (section 4.1). Today the HERB model is known as WeedSoft (Neeser et al., 2004) and is a successful decision-support tool for Nebraska growers.

4.4.2 Minnesota and Michigan: The WEEDSIM Model Lineage

The story of the WEEDSIM model begins with a study published by Swinton and King (1994), where, again equation [2.8] was utilized, but maximization was sought over a multiple-season planning horizon (see section 2.4.4). Similar to HERB, a yield loss model of the following familiar form was used:

$$Y = Y_{wf}\left(1 - \frac{\sum_{i=1}^{n} \kappa_i N_i}{1 + \sum_{i=1}^{n} \kappa_i N_i / A}\right)$$

In the calculation of N_i, however, this variable was divided into a series of cohorts:

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$$N_i = \sum_{j=1}^{3} N_{ij}$$

where the three stages were prior to crop planting, after crop planting, and after post-emergence weed control. Each cohort was model thus:

$$N_{ij,t} = \left(1 - \varepsilon_{ij,POST}\right)\left(1 - \varepsilon_{ij,PRE}\right)\alpha_{ij} S_{i,t-1}$$

where the seed bank in the previous year for species i ($S_{i,t-1}$) is multiplied by a emergence proportion α_{ij} for species i over the j^{th} time period. This emergence proportion is calculated according to cumulative degree days. This was then multiplied by pre-emergence and post-emergence efficacies, where in both cases ε_{ij} would be equal to the herbicide efficacy ε_i only if the herbicide were to have been utilized and applied to that cohort. Otherwise, ε_i would be set to zero. Lastly, seed bank dynamics were as follows:

$$S_{i,t} = \left(1 - \mu_s - \sum_{j=1}^{3} \alpha_{ij}\right) S_{i,t-1} + \sum_{j=1}^{3} \phi_{ij} N_{ij,t}$$

where an annual seed bank mortality (μ_s) is observed along with losses to the three emergence cohorts, and for calculations of seed rain the three cohorts of mature plants $N_{ij,t}$ are allowed to have three separate fecundities ϕ_{ij}.

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FIGURES 4.9 and 4.10 from Swinton and King (1994) describe some very significant findings. Both show recommendations maps for different density combinations of foxtail and broadleaf (pigweed and lambsquarters) populations. FIGURE 4.9, however, shows these recommendations based upon a planning horizon of two years, whereas FIGURE 4.10 shows the same for a planning horizon of only one year. The figures show different answers, and in particular FIGURE 4.11 illustrates that at least for foxtail seed banks the two year planning horizon provides a superior long-term solution. Swinton et al. (1994) examined year-to-year parameter variation of the yield loss equation, and found that although season-specific variation was observed for the weed-free yield parameter Y_{wf}, the other competition parameters appeared to be relatively stable.

Forcella et al. (1996) validated WEEDSIM in a multiple-year study in corn and soybean crops, finding that the model recommendations adequately controlled weeds, maintained crop yields, increased gross margins, and decreased weed management costs and environmental risks. Buhler et al. (1996) tested the model specifically in corn, and although did not observe an increase in gross margins, did observe adequate weed control and crop yield maintenance as well as a similar reduction in herbicide usage. Similar success with applications to soybean crops was observed by Buhler et al. (1997).

The WEEDSIM model has been very successful and has been recently applied to Michigan as well (Renner et al., 1999).

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4.4.3 Colorado: The GWM Model Lineage

The acronym GWM stands for "General Weed Model" and describes a very successful model developed under L. Wiles as the principal investigator. It will be described in detail, but in the second portion of this subsection. The Colorado model lineage actually begins with another model known as WEEDCAM, which began with a landmark paper by King et al. (1986), which introduced an empirical model which had a series of parameters all of which were obtainable via linear regression. For a given species i in year t seedlings were calculated thus:

$$G_{i,t} = \alpha_i S_{i,t} + \delta_{PRE,t}(1-\varepsilon_{PRE,i})S_{i,t} + \delta_{PRE,t-1}(1-\varepsilon_{PRE-1,i})S_{i,t}$$

where it was considered that the weeds could be effectively represented as two "species" – grasses ($i = 1$) and broadleaves ($i = 2$). In the above equation $\delta_{PRE,t}$ is a decision variable with a value of 1 if a preemergence herbicide is applied in year t and is zero otherwise. The variables $\varepsilon_{PRE,i}$ and $\varepsilon_{PRE\text{-}1,i}$ represent the efficacies that the preemergence herbicide has on species i in the present year and in the following year, respectively. Since the postemergence herbicide was selective to broadleaves, then:

$$N_{1,t} = G_{1,t}$$

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The efficacy of the postemergence herbicide was allowed to vary with broadleaf seedling density:

$$\varepsilon_{POST,t} = \bar{\varepsilon}_{POST,t} + \beta_{POST} G_{2,t}$$

resulting in the following calculation for mature broadleaf density:

$$N_{2,t} = \left(1 - \delta_{POST,t} \varepsilon_{POST,i}\right) G_{2,t}$$

where $\varepsilon_{POST,i}$ and $\delta_{POST,t}$ denote the efficacy of the postemergence herbicide and a decision variable for postemergence herbicide application in year t, respectively. Seed bank dynamics were represented thus:

$$S_{i,t+1} = \left(1 - \mu_{s,i}\right) S_{i,t} + \phi_i N_{i,t}$$

where fecundity and seed bank mortality are represented by the usual variables ϕ and μ_s, respectively. Crop yield loss and net profit equations were similar to those described before.

Of some significance here is the fact that the following parameters and expressions are directly obtainable via linear regression:

$$\alpha_i$$

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$$\left(1-\varepsilon_{PRE,i}\right)$$

$$\left(1-\varepsilon_{PRE-1,i}\right)$$

$$\bar{\varepsilon}_{POST,t}$$

$$\beta_{POST}$$

$$\left(1-\varepsilon_{POST,i}\right)$$

$$\left(1-\mu_{s,i}\right)$$

$$\phi_i$$

and were obtained by the authors for grass and broadleaf weeds in corn towards the relative evaluation of four long-term weed management strategies:

1. Apply preemergent herbicide every year
2. Apply preemergent herbicide in alternate years
3. Apply preemergent herbicide in alternate years with flexible usage of postemergent herbicide
4. Apply flexible usage of both preemergent and postemergent herbicides

The flexible use strategy (4) was in all situations found to be the option resulting in the highest annualized net return (see section 2.4.4), with the fixed strategy (1) being the least desirable. Placement of second and third place among the other strategies depended upon the weed densities. Demonstrated additional decision-making success similar to that found with the WEEDSIM model in the previous subsection was found by

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Lybecker et al. (1991) as well as Schweizer et al. (1992), both studies in corn. Vangessel (1995) and (1996) utilized WEEDCAM for the evaluation of various integrated weed management options in corn, involving both herbicides and tillage practices.

GWM was introduced with Wiles et al. (1996). It was presented as an event-based model that represented a given cropping season as a sequence of milestone events, some of them management-related:

- Planting
- Harvest
- Post-Emergence Herbicide Application
- Pre-Emergence Herbicide Application

and some of them biological in nature:

- End of Crop Critical Weed-Free Period
- Begin Suppression of Further Weed Emergence by Crop Canopy
- End of Pre-Emergence Herbicide Activity

Like the HERB model, weed emergence was divided into three cohorts, with the middle cohort being the one that emerges during the crop's critical period. Mature weed densities were calculated based upon the efficacies of control processes, and yield loss, net profit, and weed seed banks were calculated according to familiar means.

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The latest generation of this model lineage is a model known as WISDEM. It is the model presented in the present work. With that in mind, since the specifics of the model structure will be discussed more in chapter 7, they are not covered in detail here.

4.5 Summary

The most popular criticism given to the science of weed population modeling is a lack of applicability. With this in mind, three major quests have been undertaken, all of which are designed to enlarge the applicability and usability of such modeling tools. They involve the application and testing of such models over multiple geographic regions, the expansion to involve the effects of agronomic practices over multiple weed species, and the embrace of errors associated with model predictions.

Towards this end, over approximately a decade and a half three major model lineages have developed. Each has succeeded in incorporating effects from multiple weed species simultaneously and has displayed promising results in regards to applicability across different seasons and geographic locations. In addition, there has been a remarkable similarity in the mathematical representation of various demographic processes. What is still largely undone is an exploration of prediction errors with these models. Doing so may elucidate the maximum extent that planning horizons can be extended in the use of these models for decision-making.

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	1994	1995	Pooled
I	1.5 (2.2)	2.0 (0.8)	2.0 (2.2)
A	.61 (.45)	.30 (.04)	.38 (.10)

TABLE 4.1, showing data from Fausey et al. (1997) for interference parameter results between corn (*Zea mays*) and giant foxtail (*Setaria faberi*). Standard errors are displayed in parentheses.

	West Lafayette, IN 1994	Urbana, IL 1957-59	East Lansing, MI 1994-95
I	1.87 (0.80)	1.36 (0.28)	1.22 (0.64)
A	0.5494 (0.0841)	0.2400 (0.0213)	0.6048 (0.2636)
	Madison, WI 1994	Brookings, SD 1995	Brookings, SD 1996
I	1.21 (0.54)	1.96 (1.50)	0.11 (0.02)
A	0.3303 (0.0496)	0.4765 (0.0963)	0.4765 (0.0963)

TABLE 4.2, showing data from Lindquist et al. (1999) for interference parameter results between corn (*Zea mays*) and giant foxtail (*Setaria faberi*) at multiple locations. Standard errors are displayed in parentheses.

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	West Lafayette, IN 1994	Urbana, IL 1957-59	East Lansing, MI 1994-95
Planting Date	154	155, 133, 125	130, 128
Seeding Rate	5.9	3.2	5.9
	Madison, WI 1994	**Brookings, SD 1995**	**Brookings, SD 1996**
Planting Date	126	144	136
Seeding Rate	8.0	6.9	6.9

TABLE 4.3, showing planting Julian dates and seeding rates for all locations in the study from Lindquist et al. (1999).

Model	Desc	R^2	R^2_{adj}	AICC
1	$I = 0.08689 + 0.30334P_{july}$	.7060	.6570	-14.6666
2	$I = -11.33934 + 0.14916T_{aug} + 0.56686P_{aug}$	.7459	.6442	-13.8335

TABLE 4.4, the top two models from the model selection process of I parameter values for corn (*Zea mays*) and giant foxtail (*Setaria viridis*) on average temperatures and total precipitation for various months in the corn growing season. These are shown with R^2 values, adjusted R^2 values, and Akaike information criteria values.

Model	Desc	R^2	R^2_{adj}	C_p	AICC
1	$A = 2.45684 - 0.029T_{aug}$	.5724	.5011	-2.45	-35.0615
2	$A = 1.77583 - 0.02822T_{may} + 0.05797P_{june}$	.6492	.5089	-0.73	-34.6449

TABLE 4.5, the top two models from the model selection process of A parameter values for corn (*Zea mays*) and giant foxtail (*Setaria viridis*) on average temperatures and total precipitation for various months in the corn growing season. These are shown with R^2 values, adjusted R^2 values, Mallow's C_p values, and Akaike information criteria values.

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Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	6577.95092	3288.97546	615.52	<.0001
Error	1597	8533.45605	5.34343		
Corrected Total	1599	15111.40696			

R-Square	Coeff Var	Root MSE	NcOverYp Mean
0.435297	22.39312	2.311586	10.32275

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Nc	1	5669.467360	5669.467360	1061.02	<.0001
Nw	1	908.483555	908.483555	170.02	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Nc	1	5669.467360	5669.467360	1061.02	<.0001
Nw	1	908.483555	908.483555	170.02	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	0.177045475	0.29497666	0.60	0.5485
Nc	1.452485566	0.04459136	32.57	<.0001
Nw	0.130516254	0.01000959	13.04	<.0001

TABLE 4.6, ANOVA table assessing linear regression results of reciprocal per-plant yield on crop and weed densities according to equation [4.2].

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Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	6602.82404	2200.94135	412.84	<.0001
Error	1596	8508.58292	5.33119		
Corrected Total	1599	15111.40696			

R-Square	Coeff Var	Root MSE	NcOverYp Mean
0.436943	22.36746	2.308937	10.32275

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Nc	1	5669.467360	5669.467360	1063.45	<.0001
Nw	1	908.483555	908.483555	170.41	<.0001
Nc*Nw	1	24.873127	24.873127	4.67	0.0309

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Nc	1	1101.067230	1101.067230	206.53	<.0001
Nw	1	1.970642	1.970642	0.37	0.5433
Nc*Nw	1	24.873127	24.873127	4.67	0.0309

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1.195600323	0.55603517	2.15	0.0317
Nc	1.285015187	0.08941565	14.37	<.0001
Nw	0.029167513	0.04797419	0.61	0.5433
Nc*Nw	0.016663719	0.00771470	2.16	0.0309

TABLE 4.7, ANOVA table assessing linear regression results of reciprocal per-plant yield on crop and weed densities according to equation [4.3].

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Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	13418.18247	1916.88321	1802.29	<.0001
Error	1592	1693.22449	1.06358		
Corrected Total	1599	15111.40696			

R-Square	Coeff Var	Root MSE	NcOverYp Mean
0.887951	9.990570	1.031302	10.32275

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Nc	1	5669.467360	5669.467360	5330.53	<.0001
Nw	1	908.483555	908.483555	854.17	<.0001
Nc*Nw	1	24.873127	24.873127	23.39	<.0001
Nw*JulPrecip	1	1922.581222	1922.581222	1807.65	<.0001
Nw*AugAvgTemp	1	3929.574037	3929.574037	3694.66	<.0001
Nc*Nw*JulPrecip	1	561.394869	561.394869	527.83	<.0001
Nc*Nw*AugAvgTemp	1	401.808304	401.808304	377.79	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Nc	1	1101.067230	1101.067230	1035.24	<.0001
Nw	1	1528.672679	1528.672679	1437.29	<.0001
Nc*Nw	1	1016.337809	1016.337809	955.58	<.0001
Nw*JulPrecip	1	49.155692	49.155692	46.22	<.0001
Nw*AugAvgTemp	1	1378.140587	1378.140587	1295.75	<.0001
Nc*Nw*JulPrecip	1	62.323412	62.323412	58.60	<.0001
Nc*Nw*AugAvgTemp	1	401.808304	401.808304	377.79	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1.19560032	0.24835667	4.81	<.0001
Nc	1.28501519	0.03993807	32.18	<.0001
Nw	11.22149305	0.29599143	37.91	<.0001
Nc*Nw	-1.30192769	0.04211662	-30.91	<.0001
Nw*JulPrecip	-0.41589792	0.06117663	-6.80	<.0001
Nw*AugAvgTemp	-0.12491806	0.00347028	-36.00	<.0001
Nc*Nw*JulPrecip	0.06899225	0.00901282	7.65	<.0001
Nc*Nw*AugAvgTemp	0.01308229	0.00067307	19.44	<.0001

TABLE 4.8, ANOVA table assessing linear regression results of reciprocal per-plant yield on crop and weed densities according to equation [4.4].

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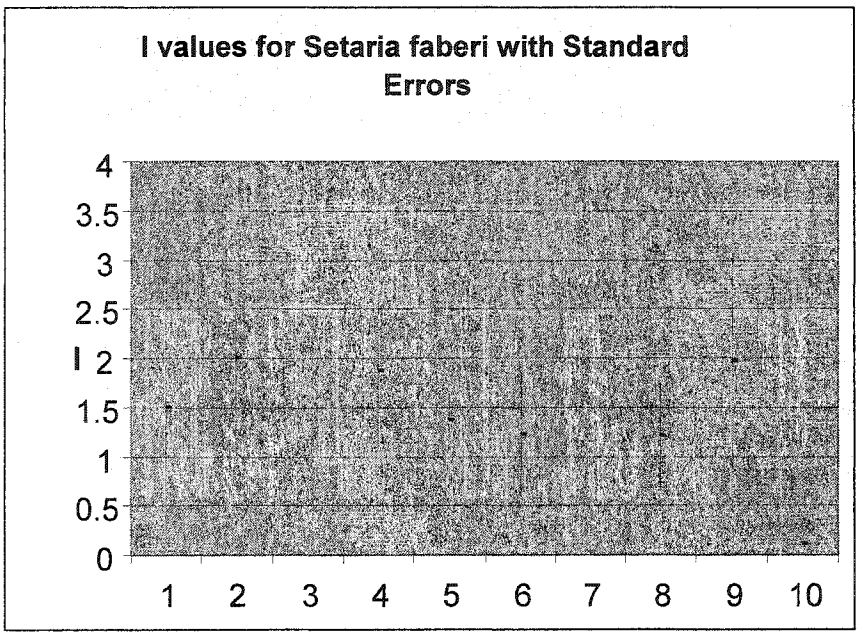

FIGURE 4.1, interference parameter *I* values between corn (*Zea mays*) and giant foxtail (*Setaria faberi*) between two studies, plotted with standard errors.

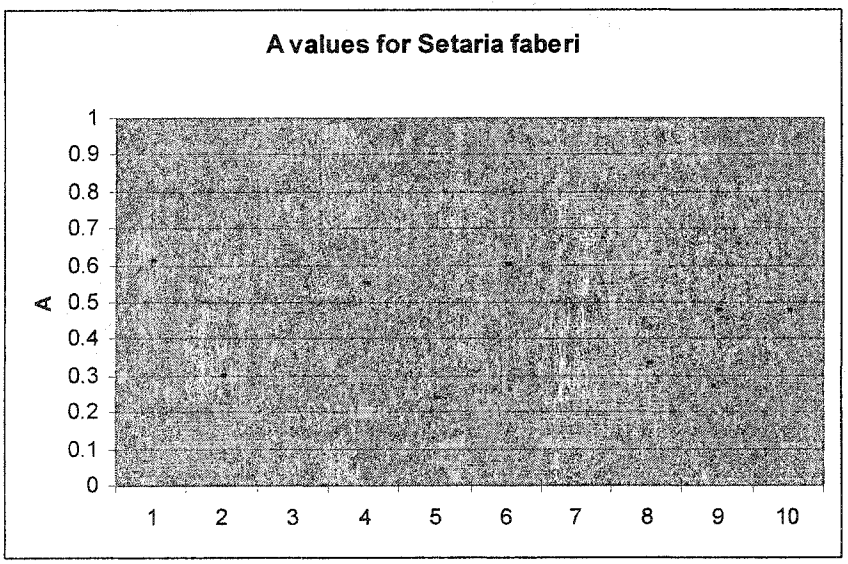

FIGURE 4.2, interference parameter *A* values between corn (*Zea mays*) and giant foxtail (*Setaria faberi*) between two studies, plotted with standard errors.

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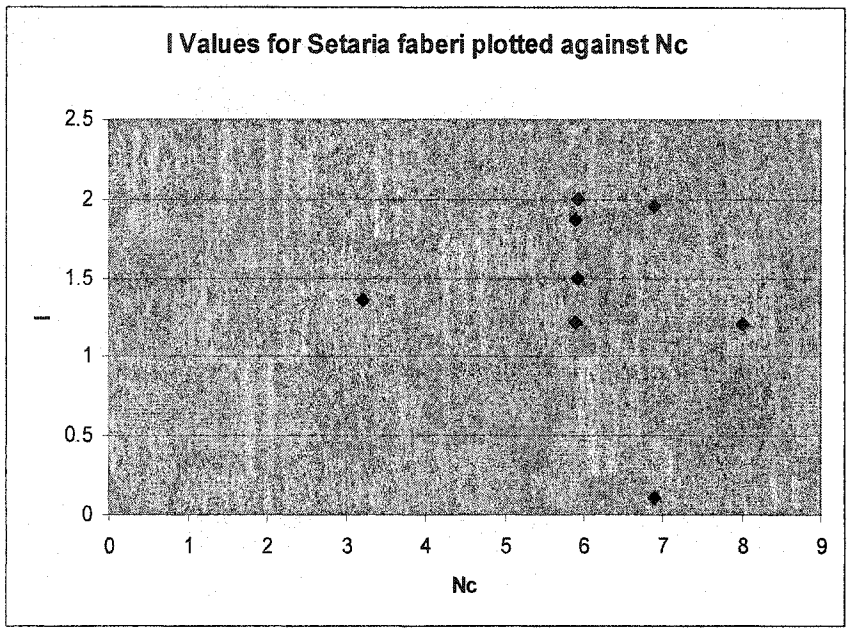

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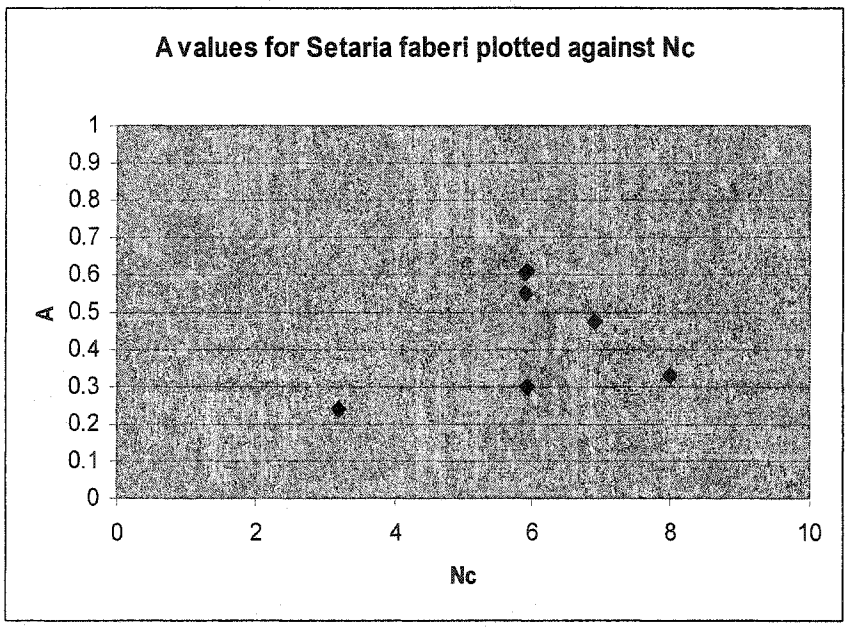

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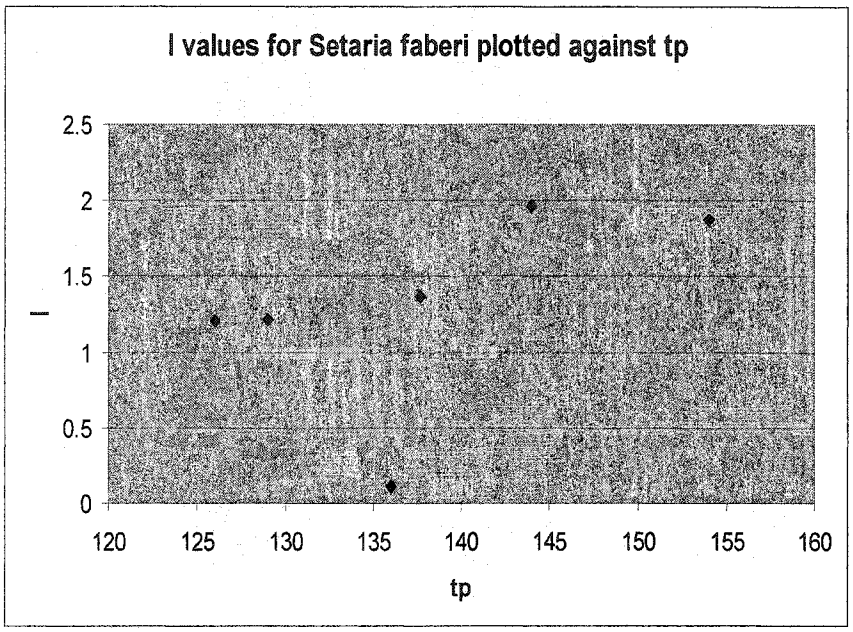

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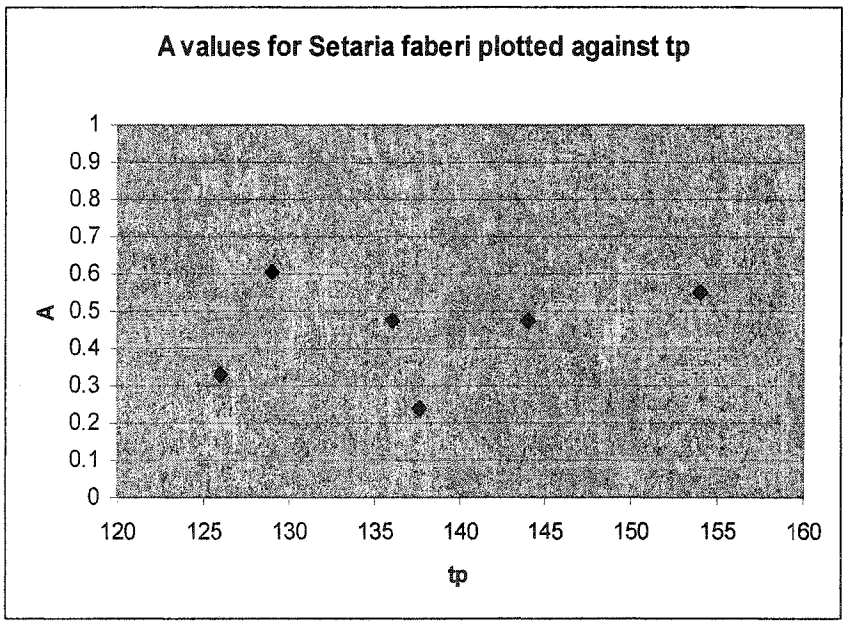

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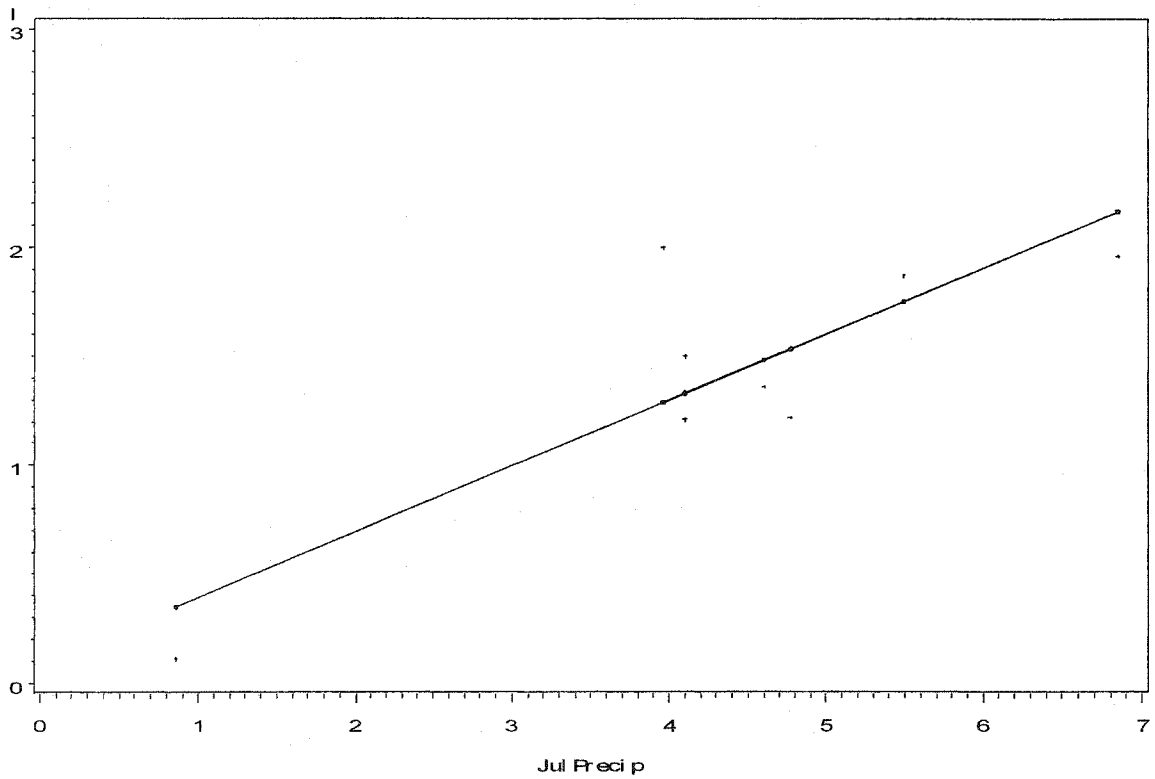

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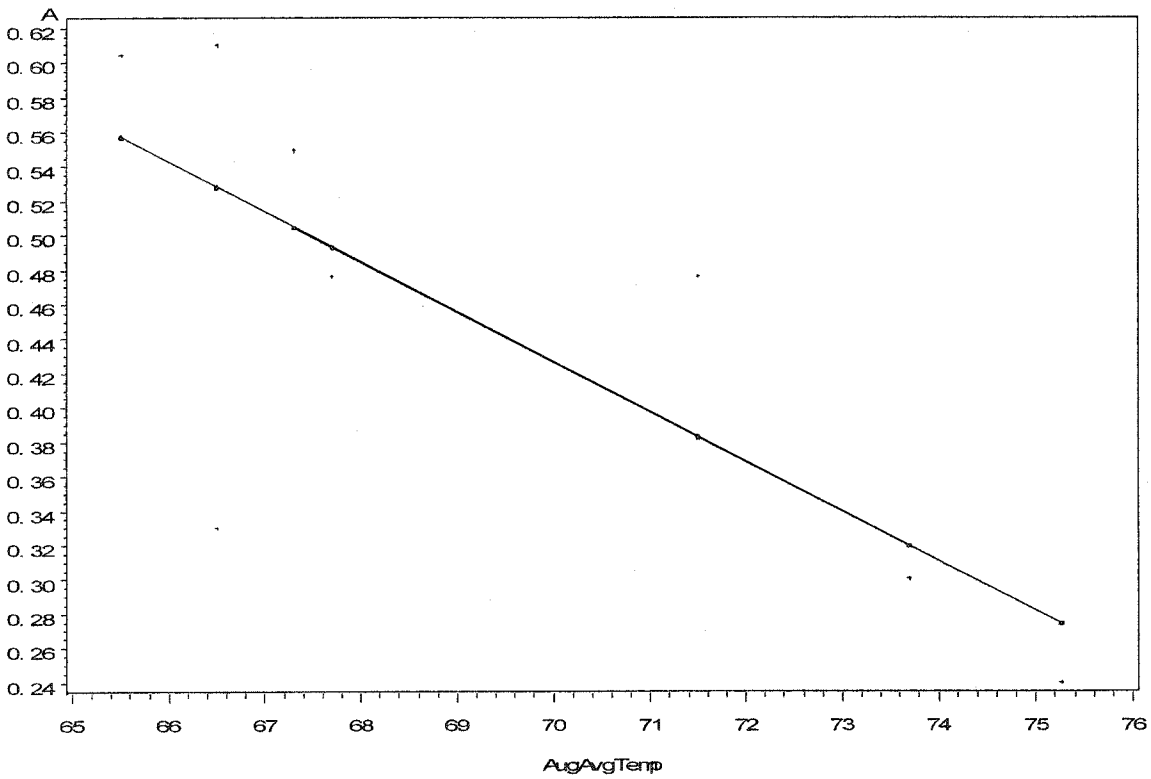

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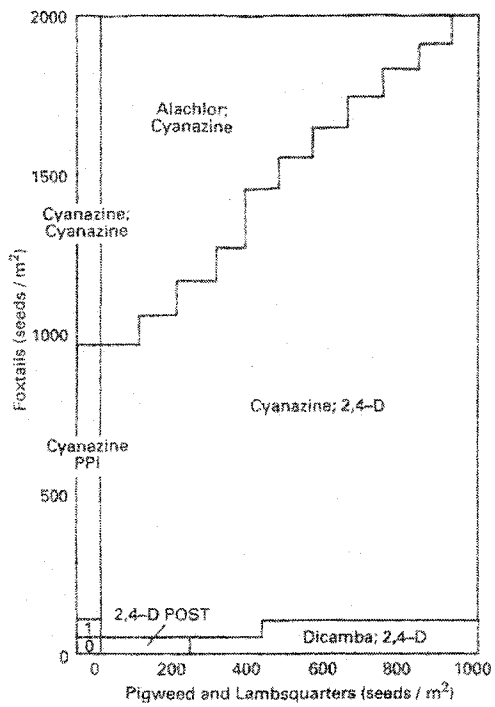

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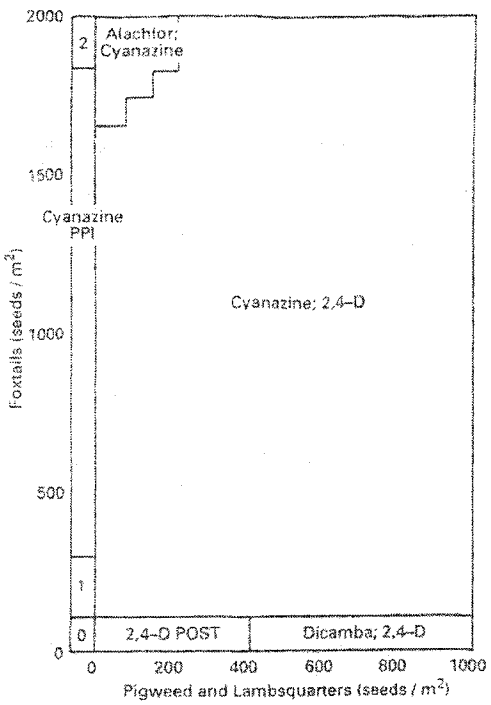

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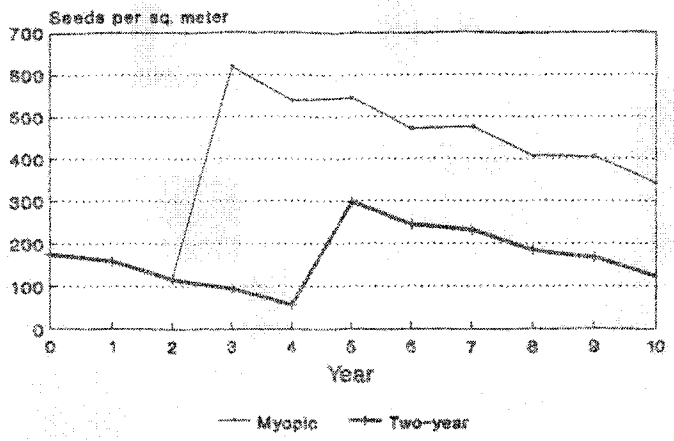

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DISSERTATION

THE USE OF THE WISDEM MODEL IN THE SIMULATION OF WEED SHIFTS IN GLYPHOSATE-TOLERANT CROPPING SYSTEMS

Volume II
Chapters 5 – 8
Appendices

Submitted by

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in partial fulfillment of the requirements
for the degree of
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Colorado State University
Fort Collins, Colorado
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Chapter 5.0
Weed Shifts in Roundup Ready™ Crops I: A Study in Expert Opinion

"Where there is no guidance the people fall, but in abundance of counselors there is victory."

Proverbs 11:14 (NAS)

5.1 Abstract

An understanding of shifts in weed populations associated with various crops, rotations, and treatment programs forms an important integral part of agronomic weed management In an effort to gain a preemptive understanding of what species are showing significant trends in Roundup Ready™ cropping systems, an extensive national survey was initiated in the summer of 2002 to sequester expert opinion on what weed species appear to be displaying the most significant shifts. Species reported as increasing in such cropping systems existed in 19 different plant families, and its most prominent genii were *Amaranthus* spp., *Chenopodium* spp., *Conyza* spp., *Ambrosia* spp., *Ipomoea* spp., *Echinochloa* spp., *Sida* spp., and *Polygonum* spp. Further opportunity was given to discuss what biological or ecological factors were believed to be responsible for the shift and what management recommendations were given. Of greatest popularity were issues of biological tolerance and pattern of emergence that underscored the importance of timely applications and the use of additional products from other herbicidal modes of action. Lastly, a quantitative analysis of the reported time frames of the weed shift

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resulted in a list of average annual growth rates of each species. Horseweed (*Conyza canadensis*) and waterhemp (*Amaranthus rudis*) showed particularly strong results in regards to the rate of increase of these species. Such surveys should prove useful and should be extended to further troubleshoot any and all upcoming weed shift issues with Roundup Ready™ crops.

5.2 Introduction

Agronomic practices can be thought of as a set of forced periodic ecological disturbances that enact differential selection pressures on various plant species. Such variable selection pressures result in shifts in weed populations, requiring an eventual modification of weed control practices to maintain effective management. Thus, a predetermined knowledge of potential weed shifts from various cropping systems provides important insight into effective long-term weed management and safeguarding of agronomic technologies.

Some formal studies of weed shifts in Roundup Ready™ (hereafter referred to as RR) crops have begun (Trucco, 2002), and some occurrences of relative biological tolerance have been documented for various species, the most significant domestic example being *Conyza canadensis* (VanGessel, 2001). Such differences in biological tolerance, resulting in a difference in the **effective kill rate** among different species, can

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certainly result in weed shifts, but are only one of several possible biological and ecological causes.

The dynamics of interspecific plant interactions documented and quantified in various crop-weed interference and replacement series studies (e.g., Lodge, 2000) illustrates an attempt to empirically represent degrees of competitive superiority that are believed to result in weed shifts. Thus, in the context of agronomic situations, it is hypothesized that a particular weed shift can occur by way of a strong **competitive ability of the weed** or more indirectly through a relatively weak **competitive ability of the crop**.

In addition, issues of the **pattern of weed emergence** can result in later emerging species avoiding control measures either partially or altogether. It is similarly hypothesized that timing of seed production via **photoperiod sensitivity** can also play a factor.

Factors relating to plant genetics are also examined as candidates. **Genetic diversity** appears to play a strong role in tolerance to auxin-based herbicides in kochia (Belles, 2004). **Introgression of traits** into weed species from other species may allow for the quick "communication" of tolerance traits into weed species through gene flow. A good example of this would be the quick introgression of ALS-tolerance into jointed goatgrass (*Aegilops cylindrica*) from ALS-tolerant winter wheat (*Triticum aestivum*) (Hanson et al., 2002). On an empirical level these positive genetic factors may be best

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detected by the degree to which the weed species has been able to demonstrate **resistance to other herbicides** in the past.

Lastly, reproductive factors are also considered. **Seed persistence** in the soil has been implicated as a major factor in weed shifts related to herbicide tolerance (Gressel and Segel, 1982). **Seed production** and **seed dispersal** have also certainly been implicated by various modeling studies (Maxwell and Ghersa, 1992). Lastly, the ability of a plant species to practice **vegetative reproduction** has also been cited as a weedy characteristic responsible for plant invasion (Radosevich et al., 1997).

The purpose of this study was twofold, to first identify potential species undergoing shifts in RR crops, and secondly to identify biological and ecological factors believed to be involved in such shifts. It was desired that the above information would be obtained quickly and efficiently, and so a survey was conducted to sequester expert opinion in this regard. This survey is described in detail in the next section.

5.3 Materials and Methods

In an effort to compile and quantitatively describe emerging expert opinion on the subject of weed shifts in RR crops, a questionnaire was developed and sent to numerous consultants in the public, private, and academic sectors throughout the United States.

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The questionnaire contained numerous copies of the forms displayed in FIGURE 5.1, where example input is also displayed. Across the top of the first form the respondent indicated the name of a single weed species that was believed to experience a significant shift in RR crops along with a statement of which cropping systems this shift was occurring, a symbol indicating either an increase or decrease, an approximate time frame of the shift, and a checkbox on whether or not this shift had actually been observed or was simply believed to occur.

In addition, the lower left portion of the form contained a forum in which the respondent could describe the ecological processes believed responsible for the shift. The categories of such processes were the same as those listed in the Introduction.

Next to each category the respondent indicated corresponding percentages describing the degree to which each process was believed to participate in the above weed shift, where the total of all percentages would be 100%. For example, if it was believed that the reason for an increase in populations of a given weed were due to late-emerging cohorts dispersing large amounts of seed over long distances, then the response might have been as follows:

Competitive Ability of the Weed

Competitive Ability of the Crop

Effective Kill Rate

Genetic Diversity

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	Introgression of Traits
50%	Pattern of Emergence
	Photoperiod Sensitivity
	Vegetative Reproduction
	Resistance to Other Herbicides
	Seed Persistence
25%	Seed Production
25%	Seed Dispersal

Lastly, in the lower right side of the form the respondents were asked to provide any further information on the weed shift as well as to comment on what management techniques would most likely abate the shift.

Each full questionnaire contained six repetitions of the above form, allowing for up to six weed shifts to be reported and discussed by each respondent. The questionnaire concluded with an open-ended question concerning what aspects of weed biology and/or ecology required the most improvement in understanding for predictions to become more reliable and accurate.

The questionnaires were sent to various individuals in the summer of 2002, and responses were received by the individuals listed in TABLE 5.1, where FIGURE 5.2 displays a geographic distribution of these responses, showing the best response in the

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western Gulf states, the western Mississippi valley, the central Great Plains, and the Pacific coast. Many thanks are extended to all those who responded.

5.4 Results and Discussion

TABLE 5.2 begins the analysis with a general roll call of plant families with species with cited increases in RR crops. Nineteen families are represented, many of which have multiple species listed. The Amaranthaceae species, listed in TABLE 5.3, include palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus rudis*), both of which have a strong showing of both citations and observed occurrences. Chenopodiaceae species, shown in TABLE 5.4, include a strong showing on lambsquarters as well as comparatively modest showings for kochia (*Kochia scoparia*) and Russian thistle (*Salsola iberica*). Species in the Asteraceae subfamily are shown in TABLE 5.5, with by far the strongest showing from horseweed (*Conyza canadensis*), which confirms the findings of VanGessel (2001). Giant ragweed (*Ambrosia trifida*) is also mentioned in multiple instances, with singular citations appearing for common ragweed (*Ambrosia artemisiifolia*), mayweed chamomile (*Anthemis cotula*), prickly lettuce (*Lactuca seriola*), and dandelion (*Taraxacum officinale*). Convolvulaceae species, shown in TABLE 5.6, were mostly in general reference to morningglory species (*Ipomoea* spp.) TABLE 5.7 shows a singular reference to horsetail (*Equisetum* spp.), and TABLE 5.8 shows three references each to copperleaf (*Acalypha* spp.) and spurge species (*Euphorbia* spp.). Grass species, shown in TABLE 5.9, include relatively strong

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showings from longspine sandbur (*Cenchrus longispinus*), barnyardgrass (*Echinochloa crus-galli*), prairie cupgrass (*Eriochloa contracta*), annual ryegrass (*Lolium multiflorum*), and volunteer RR wheat (*Triticum aestivum*). The citation of annual ryegrass also confirms previous findings of tolerant biotypes (Powles et al., 1998). Malvaceae species (TABLE 5.10) show a strong showing of prickly sida (*Sida spinosa*), with singular showings of velvetleaf (*Abutilon theophrasti*), common mallow (*Malva neglecta*), and volunteer RR cotton (*Gossypium hirsutum*). Five instances of polygonum species citations (TABLE 5.11) are reported with two of them specifically citing wild buckwheat (*Polygonum convolvulus*). Nightshade species citations (TABLE 5.12) included hairy nightshade (*Solanum sarrachoides*) and eastern black nighshade (*Solanum ptycanthum*).

Species with reported decreases in RR crops were almost as diverse among plant families as those with reported increases. Nine families are listed in TABLE 5.13, with most of the significant families from TABLE 5.2 again listed. TABLE 5.14 lists these citations by species for all families in TABLE 5.13. The more popular choices were kochia, Canada thistle (*Cirsium arvense*), common cocklebur (*Xanthium strumarium*), wild oat (*Avena fatua*), and johnsongrass (*Sorgum halepense*).

For the more prominently cited species, additional insight was sought via a geographic depiction of their responses. FIGURE 5.3 shows such a depiction for the responses citing increases of horseweed. States in the southern central Great Plains are listed along with Washington, Delaware, and states all along the Mississippi valley,

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together representing locations associated with RR corn, soybeans, wheat, and cotton. The citation in Delaware has been further described in the study by VanGessel (2001).

States showing cited increases of waterhemp (FIGURE 5.4) were generally in the eastern Great Plains and in the northern Mississippi valley. States showing increase in ragweed species (FIGURE 5.5) were localized more in the upper Midwest.

States showing increases of morningglory species (FIGURE 5.6) were California, Kansas, the mid-Mississippi valley, and in southern states along the Gulf of Mexico. States showing increases in palmer amaranth (FIGURE 5.7) were generally in the same general area, but to a lesser degree.

Increases in buckwheat species (FIGURE 5.8) were generally cited in states in the northern Great Plains and northern Mississippi valley. The same was generally observed for common lambsquarters (FIGURE 5.9) with the latter also appearing in Pacific coastal states.

Barnyardgrass (FIGURE 5.10) was cited as increasing in Mississippi as well as in states along the Pacific. Prickly sida (FIGURE 5.11) was cited as increasing in the lower to mid-Mississippi valley, and nightshades (FIGURE 5.12) were cited as increasing in two central Great Plains states.

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Lastly, FIGURES 5.13 and 5.14 show similar geographic locations of *Commelina* spp. and *Eriochloa* spp., respectively. The presence of rising *Commelina* spp. populations in Georgia is consistent with the findings of Culpepper and Flanders (2003).

In response to the portion of the questionnaire designed to assess relevant ecological processes, percentages for all survey responses were averaged, the results of which are displayed in FIGURE 5.15. Clearly the two most significant ecological elements indicated are effective kill and pattern of emergence, implying that in most instances these shifts are believed to be due either to differences in biological tolerance or differences in emergence patterns that allow for avoidance of the herbicide application. This was confirmed by the written commentary provided by many respondents, which focused largely on responding to these issues by implementing more timely applications and rotating the mode of action to include an herbicide for which tolerance is not an issue for the given weed species.

Lastly, a quantitative assessment of the reported time scales of the aforementioned weed shifts was performed. A growth rate was calculated from the time scale by assuming that a cited weed shift involved a density increase by an order of magnitude. Such population dynamics are assumed to be describable by the following equation:

$$N_t = \lambda N_{t-1}$$

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where λ describes an annual growth rate for the shifting species. Thus, for a weed shift involving an increase by a factor of 10 over a cited period of τ years:

$$N_t = \lambda^{\tau} N_0 = 10 N_0$$

Thus, this growth rate can be calculated as follows:

$$\lambda = \sqrt[\tau]{10}$$

For each weed species, values of this annual growth rate were averaged over all responses providing explicit shift time frames. For two weed species, velvetleaf and kochia, the direction of the shift was dependent upon cropping situation, and so two separate averages were calculated. The results are displayed in TABLE 5.15, where the most rapidly increasing species are displayed first with annual growth rates displayed in the third column. These results should be observed with some caution, for many of the averages are based on a single data point, and those that are based upon multiple data points are averaged across multiple cropping systems and geographic locations. However, having stated this as well as acknowledging the inevitably large amount of error that must be presumed from data of this origin, it was nevertheless interesting to find the extent of agreement among these multiple responses. Those averages requiring three or more data values were listed in boldface.

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5.5 Conclusions

Two of the cited species, *Conyza canadensis* and *Lolium multiflorum*, have been cited by previous authors as tolerant to glyphosate (Powles et al., 1998; VanGessel, 2001). For these species, this research provides further confirmation of this, and assigns a geographic dimension of its effects. In addition, numerous other species are similarly implicated and should be further investigated as potential problems in RR crops. These other species exist in 19 different plant families, and its most prominent genii are *Amaranthus* spp., *Chenopodium* spp., *Ambrosia* spp., *Ipomoea* spp., *Echinochloa* spp., *Sida* spp., and *Polygonum* spp. Geographic locations of species-specific increases appear to centralize most often in the eastern Great Plains and Mississippi valley. It is uncertain as to whether this geographic concentration is reflective of the geographic region showing the highest concentration of responses (FIGURE 5.2) or of the fact that this region tends to involve the highest extent of glyphosate usage.

In response to reported time scales for each weed shift, annual growth rates for many weed species have been calculated, and are displayed in TABLE 5.15. Of interest is the fact that from this data alone a simple model is implied, where if the starting densities of a series of weed species are known for a given location, described together here as a vector having one entry for each species:

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$$\mathbf{N} = \begin{bmatrix} N_1 \\ N_2 \\ \vdots \\ N_n \end{bmatrix}$$

where in this case n species are listed, then if the growth rates in TABLE 5.15 are arranged in a matrix as follows:

$$\mathbf{A} = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & 0 & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{bmatrix}$$

then populations in the following year would be calculated by matrix multiplication:

$$\mathbf{N}_{t+1} = \mathbf{A}\mathbf{N}_t$$

and the data in TABLE 5.15 can be utilized as a simple prediction tool. Such "expert-based" models have been theorized by Dunan et al. (1999) as a powerful technique, since the data is easily obtainable and the implementation is relatively simplistic.

Glyphosate has become one of the most prolific herbicides nationwide (Battaglin et al., 2003). Its usage has become associated with some equally prolific cropping system technologies. For the purpose of safeguarding the effective usage of these agronomic tools studies like the one shown here will need to be continued and expounded upon to

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allow for the continued avoidance of costly weed shifts and the abatement of large-scale tolerance.

5.6 Acknowledgements

In addition to all the respondents listed in TABLE 5.1, I would like to thank Dr. Claudio Dunan, Dr. Les Glasgow, Dr. Phil Westra, and Dr. Lori Wiles for their assistance in the development of the questionnaire.

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5.7 References

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Respondent Name	Organization
Dr. Chris Boerboom	University of Wisconsin
Dr. Rick Boydston	Syngenta Corporation
Dr. Stanley Culpepper	University of Georgia
Dr. Peter Dotray	Texas Tech University
Dr. Kirk Howatt	North Dakota State University
Dr. Bill Johnson	University of Missouri
Dr. Mark Loux	Ohio State University
Dr. James Mickelson	Montana State University
Dr. Brett Miller	Syngenta Corporation
Dr. Steve Miller	University of Wyoming
Dr. Craig Nichols	Syngenta Corporation
Dr. Michael D. K. Owen	Iowa State University
Dr. Bob Parker	Syngenta Corporation
Dr. Dallas Peterson	Kansas State University
Dr. Daniel H. Poston	Delta Research & Ext Ctr, MS
Dr. Dave Regehr	Kansas State University
Dr. David R. Shaw	Mississippi State University
Dr. Reid J. Smeda	University of Missouri
Dr. Kenneth L. Smith	University of Arkansas
Dr. Philip Stahlman	Kansas State University
Dr. Denny Stam	Syngenta Corporation
Dr. Dave Thomas	Syngenta Corporation
Dr. Michael Urwiler	University of IL at Urbana-Champaign
Dr. Mark Van Gessel	University of Delaware
Dr. Ron Vargas	University of California at Davis
Dr. P. Roy Viridine	Louisiana State University
Dr. Philip Westra	Colorado State University
Dr. Steve Wright	University of California at Davis
Dr. Joe Yenish	Washington State University
Dr. Brian Young	Southern Illinois University

TABLE 5.1, List of survey respondents.

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Family	Number of Hits	
	Cited	Cited and Observed
Amaranthaceae	14	8
Caryophyllaceae	2	2
Chenopodiaceae	10	2
Commelinaceae	3	2
Compositae-Asteraceae	21	12
Convolvulaceae	12	6
Cyperaceae	1	1
Equisetaceae	1	1
Euphorbiaceae	6	4
Gramineae-Poaceae	20	4
Labiatae-Lamiaceae	2	2
Malvaceae	7	1
Papilionaceae-Fabaceae	2	2
Phytolaccaceae	1	1
Polygonaceae	5	1
Primulaceae	1	1
Solanaceae	3	1
Violaceae	1	1
Zygophylaceae	1	0
TOTAL	113	52

TABLE 5.2, Plant families showing species increasing in RR technology.

Genus	Species	Number of Hits	
		Cited	Cited and Observed
Amaranthus	*Amaranthus palmeri*	5	3
	Amaranthus rudis	9	5

TABLE 5.3, Amaranthaceae species showing increases in RR technology.

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Genus	Species	Number of Hits	
		Cited	Cited and Observed
Chenopodium	*Chenopodium album*	4	2
	Chenopodium L. *spp.*	2	0
Kochia	*Kochia scoparia*	2	0
Salsola	*Salsola iberica*	2	0

TABLE 5.4, Chenopodiaceae species showing increases in RR technology.

Genus	Species	Number of Hits	
		Cited	Cited and Observed
Ambrosia	*Ambrosia artemisiifolia*	1	1
	Ambrosia trifida	5	3
Anthemis	*Anthemis cotula*	1	0
Conyza	*Conyza canadensis*	12	7
Lactuca	*Lactuca seriola*	1	0
Taraxacum	*Taraxacum officinale*	1	1

TABLE 5.5, Compositae-Asteraceae species showing increases in RR technology.

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Genus	Species	Number of Hits	
		Cited	Cited and Observed
Ipomoea	*Ipomoea* spp.	10	5
	Ipomoea hederacea	1	0
	Ipomoea lacunose	1	1

TABLE 5.6, Convolvulaceae species showing increases in RR technology.

Genus	Species	Number of Hits	
		Cited	Cited and Observed
Equisetum	*Equisetum* spp.	1	1

TABLE 5.7, Equisetaceae species showing increases in RR technology.

Genus	Species	Number of Hits	
		Cited	Cited and Observed
Acalypha	*Acalypha* L. spp.	2	2
	Acalypha ostryifolia	1	1
Euphorbia	*Euphorbia* spp.	1	0
	Euphorbia dentata	2	1

TABLE 5.8, Euphorbiaceae species showing increases in RR technology.

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Genus	Species	Number of Hits	
		Cited	Cited and Observed
Cenchrus	*Cenchrus longispinus*	2	1
Chloris	*Chloris verticillata*	1	0
Digitaria	*Digitaria* spp.	1	0
Echinochloa	*Echinochloa crus-galli*	4	1
Eriochloa	*Eriochloa contracta*	3	0
	Eriochloa villosa	1	1
Lolium	*Lolium multiflorum*	3	1
Setaria	*Setaria* spp.	1	0
	Setaria faberi	1	0
Triticum	*Triticum aestivum*	2	0
Vulpia	*Vulpia myuros*	1	0

TABLE 5.9, Graminae-Poaceae species showing increases in RR technology.

Genus	Species	Number of Hits	
		Cited	Cited and Observed
Abutilon	*Abutilon theophrasti*	1	0
Gossypium	*Gossypium hirsutum*	1	0
Malva	*Malva neglecta*	1	0
Sida	*Sida spinosa*	4	1

TABLE 5.10, Malvaceae species showing increases in RR technology.

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Genus	Species	Number of Hits	
		Cited	Cited and Observed
Polygonum	*Polygonum* spp.	3	0
	Polygonum convolvulus	2	1

TABLE 5.11, Polygonaceae species showing increases in RR technology.

Genus	Species	Number of Hits	
		Cited	Cited and Observed
Solanum	*Solanum sarrachoides*	1	1
	Solanum ptycanthum	1	0
	Solanum spp.	1	0

TABLE 5.12, Solanaceae species showing increases in RR technology.

Family	Number of Hits	
	Cited	Cited and Observed
Amaranthaceae	1	1
Chenopodiaceae	2	0
Compositae-Asteraceae	7	4
Convolvulaceae	1	0
Cyperaceae	1	0
Gramineae-Poaceae	8	1
Labiatae-Lamiaceae	1	1
Malvaceae	1	1
Pedaliaceae	1	0
TOTAL	23	8

TABLE 5.13, Plant families showing species decreasing in RR technology.

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Family	Genus	Species	Number of Hits	
			Cited	Cited and Observed
Amaranthaceae	Amaranthus	*Amaranthus palmeri*	1	1
Chenopodiaceae	Kochia	*Kochia scoparia*	2	0
Compositae-Asteraceae	Ambrosia	*Ambrosia grayi*	1	1
		Ambrosia artemisiifolia	1	0
	Cirsium	*Cirsium arvense*	3	2
	Xanthium	*Xanthium strumarium*	2	1
Convolvulaceae	Convolvulus	*Convolvulus arvensis*	1	0
Cyperaceae	Cyperus	*Cyperus rotundus*	1	0
Gramineae-Poaceae	Avena	*Avena fatua*	2	0
	Cynodon	*Cynodon dactylon*	1	0
	Erichloa	*Eriochloa villosa*	1	0
	Lolium	*Lolium multiflorum*	1	0
	Sorghum	*Sorghum halepense*	2	1
		Sorghum bicolor	1	0
Labiatae-Lamiaceae	Salvia	*Salvia reflexa*	1	1
Malvaceae	Abutilon	*Abutilon theophrasti*	1	1
Pedaliaceae	Proboscidea	*Proboscidea louisianca*	1	0

TABLE 5.14, Species from all families showing decreases in RR technology.

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Weed Name	Weed Shift Timeframe (Years)	Annual Rate (λ)	Number of Citations
Hemp sesbania	1.00	10.00	1
Volunteer Wheat	1.33	5.62	2
Windmillgrass	2.00	3.16	1
Rattail fescue	2.00	3.16	1
Punctureviné	2.50	2.51	1
Palmer pigweed	3.00	2.15	1
Nutsedge	3.00	2.15	1
Pokeweed	3.00	2.15	1
Waterhemp	**3.03**	**2.14**	**7**
Barnyardgrass	3.21	2.05	2
Prickly sida	**3.43**	**1.96**	**4**
Nightshade spp.	**3.46**	**1.94**	**3**
Horseweed	**3.53**	**1.92**	**9**
Russian thistle	3.75	1.85	2
Prairie cupgrass	**3.75**	**1.85**	**3**
Palmer amaranth	**3.87**	**1.81**	**4**
Horsetail	4.00	1.78	1
Morningglory spp.	**4.08**	**1.76**	**10**
Euphorbia spp.	**4.19**	**1.73**	**3**
Kochia (in Winter Crops)	4.24	1.72	2
Commelina spp.	**4.44**	**1.68**	**3**
Longspine sandbur	4.44	1.68	2
Common mallow	4.50	1.67	1

TABLE 5.15, species from survey with shift timeframes, rates of increase, and number of citations from the survey, shown in descending order according to rate of increase.

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Weed Name	Weed Shift Timeframe (Years)	Annual Rate (λ)	Number of Citations
Lambsquarters	**4.54**	**1.66**	**4**
Giant Ragweed	**4.66**	**1.64**	**6**
Smartweed spp.	**4.86**	**1.61**	**3**
Velvetleaf (in Corn)	5.00	1.58	1
Henbit	5.00	1.58	1
Chickweed	5.00	1.58	1
Field pansy	5.00	1.58	1
Wild buckwheat	5.71	1.50	2
White campion	6.00	1.47	1
Prickly lettuce	6.00	1.47	1
Marestail	7.50	1.36	1
Copperleaf	10.00	1.26	2
Wild oat	-10.00	0.79	1
Velvetleaf (in Corn/Soybeans)	-6.00	0.68	1
Woolyleaf bursage	-5.00	0.63	1
Devil's claw	-5.00	0.63	1
Lanceleaf sage	-5.00	0.63	1
Annual ryegrass	-5.00	0.63	1
Kochia (in Spring Crops)	-4.44	0.60	2
Common ragweed	-4.00	0.56	1
Common cocklebur	-3.73	0.54	2
Canada thistle	**-3.67**	**0.53**	**3**
Shattercane	-3.00	0.46	1
Woolly cupgrass	-2.50	0.40	1

TABLE 5.15, continued.

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Weed Species	Crop Rotation	Tillage System	Other Weeds	+,-	Time in Years	Observed?
(Example) Horseweed	Corn / Soybeans	NT / RT	Pigweed, Lambsquarter	+	3 years	☒
						☐

% Importance	Factor
	Competitive ability of the weed. The ability of the weed to compete with the crop and other weeds for resources.
	Competitive ability of the crop. The ability of the crop to compete with weeds for resources.
	Effective Kill Rate. Percent weed control provided by a given herbicide program.
	Genetic Diversity. The degree of genetic variation in a weed population.
	Introgression of Traits. The ability to self-pollinate.
	Pattern of Emergence. Weed emergence pattern(s) during the growing season.
	Photoperiod sensitivity. The influence of photoperiodicity on late-season seed production.
	Vegetative Reproduction. The ability to reproduce vegetatively in addition to reproduction by seeds.
	Resistance to Other Herbicides. Whether the weed has already developed resistance to other herbicides.
	Seed Persistence. The ability of the seed to remain dormant for long periods of time, avoiding mortality.
	Seed Production. Amount of seed produced.
	Seed Dispersal. Patterns of seed dispersal.
	Other. Please specify:
100%	**Total**

What would you recommend to slow or stop this weed shift, and why? What aspects of the biology or population dynamics of this weed would be affected by your recommendation plan?

Do you have any other comments regarding this weed shift? If so, what are they?

FIGURE 5.1, The general questionnaire format which was repeated six times for each respondent. It should be noted that in particular for the latter two questions additional space was provided than what is shown here, since the questionnaire was oriented in a landscape format.

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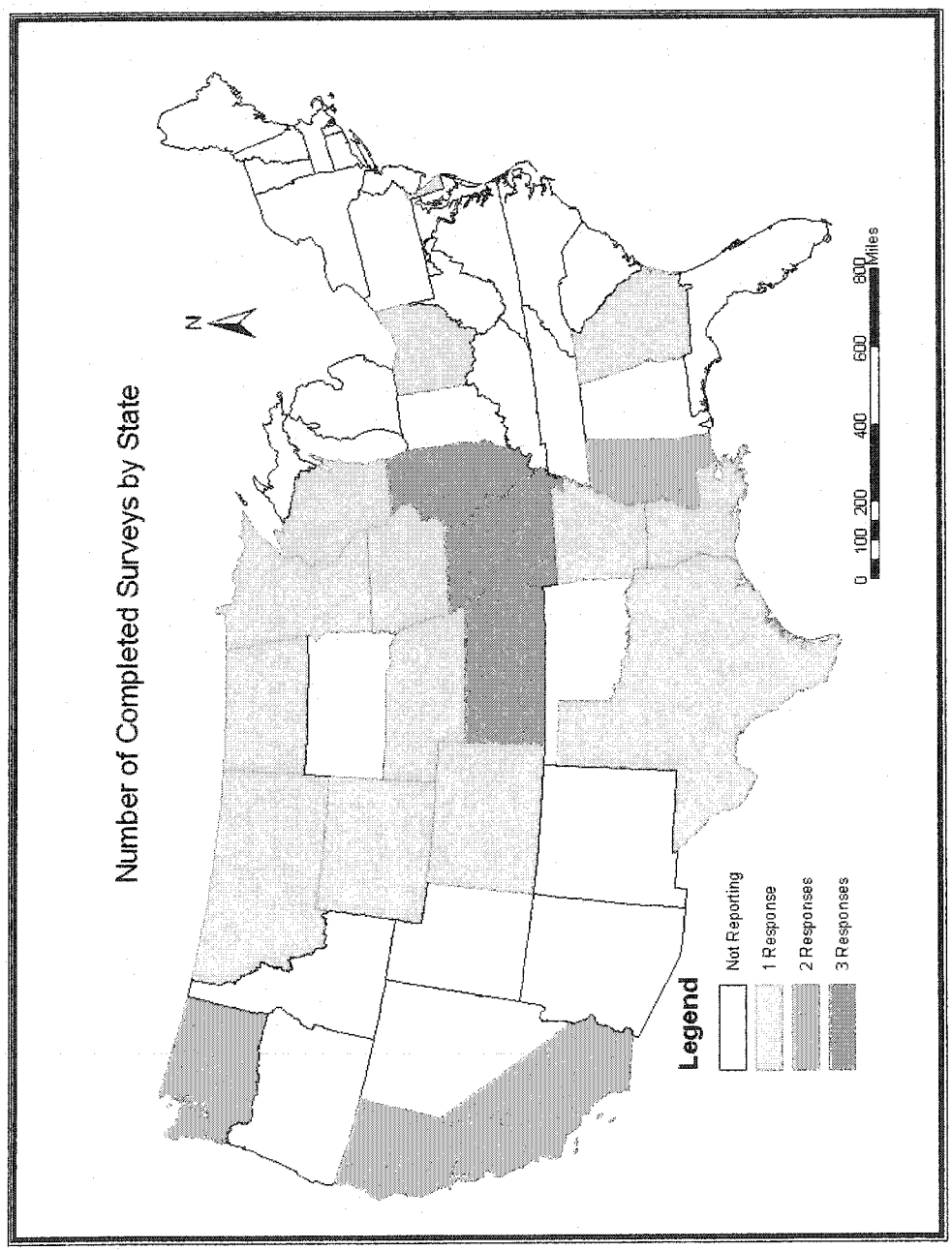

FIGURE 5.2, Total questionnaire responses by state.

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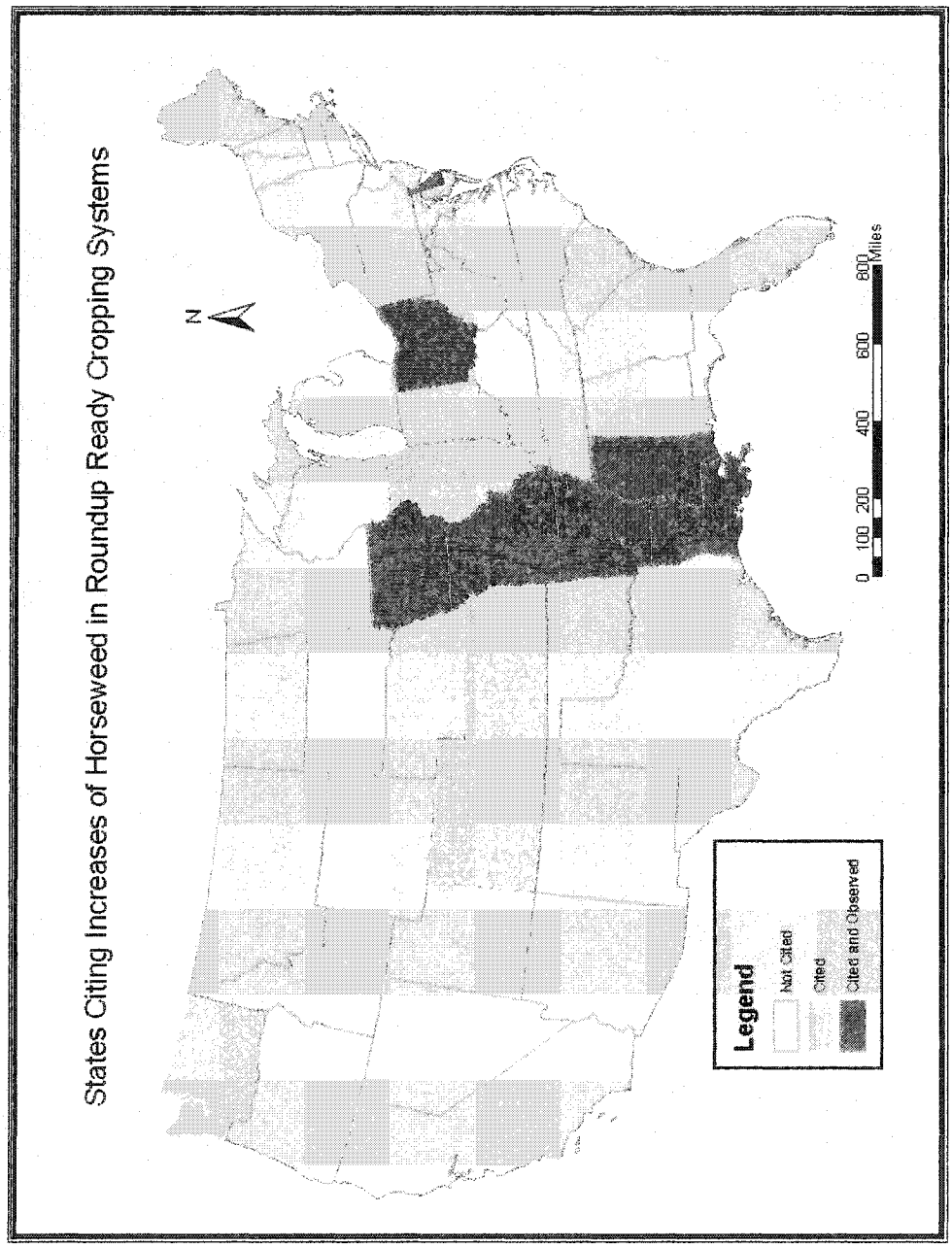

FIGURE 5.3, states reporting increases of horseweed (*Equisetum arvense*) in Roundup Ready™ crop technology.

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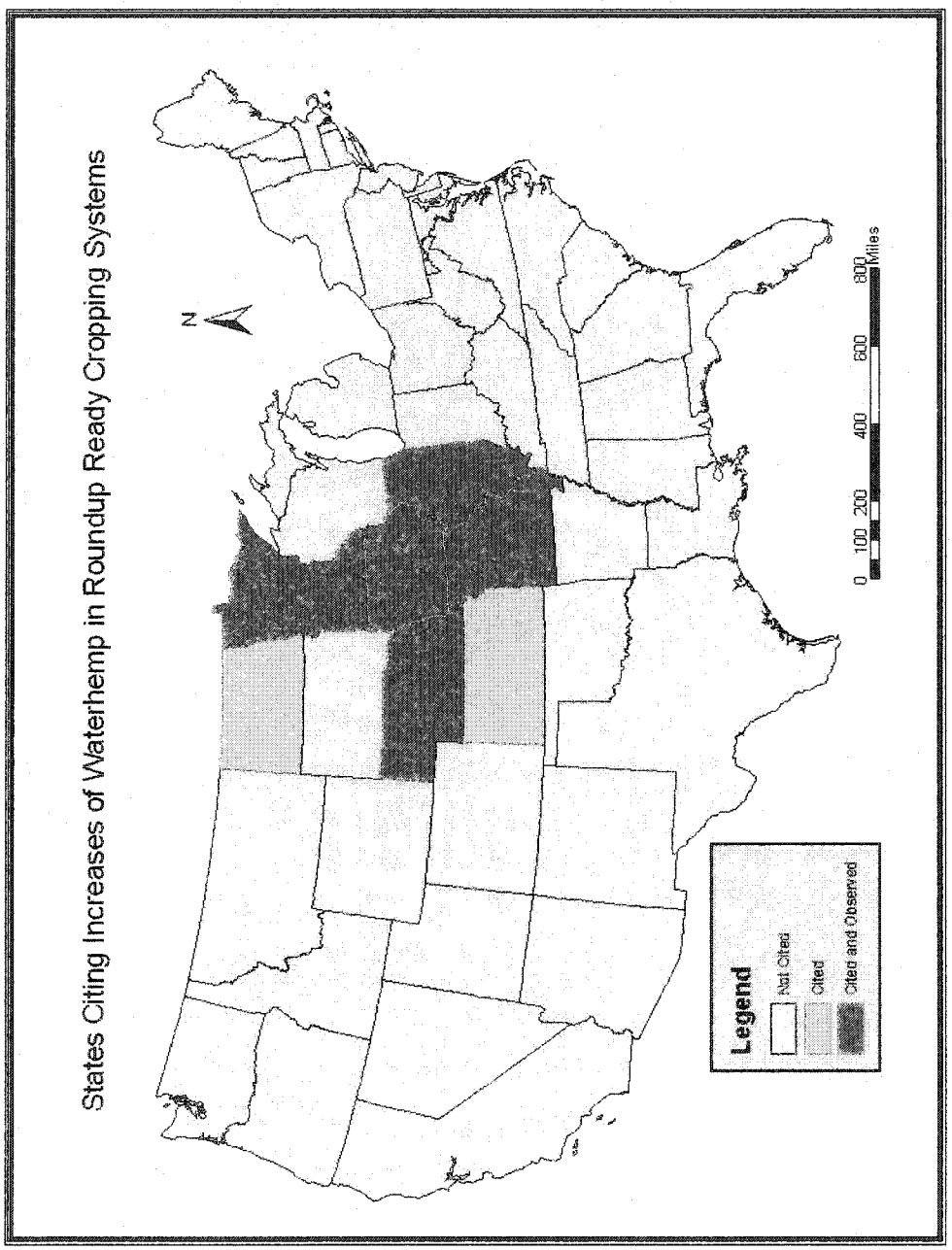

FIGURE 5.4, states reporting increases of waterhemp (*Amaranthus rudis*) in Roundup Ready™ crop technology.

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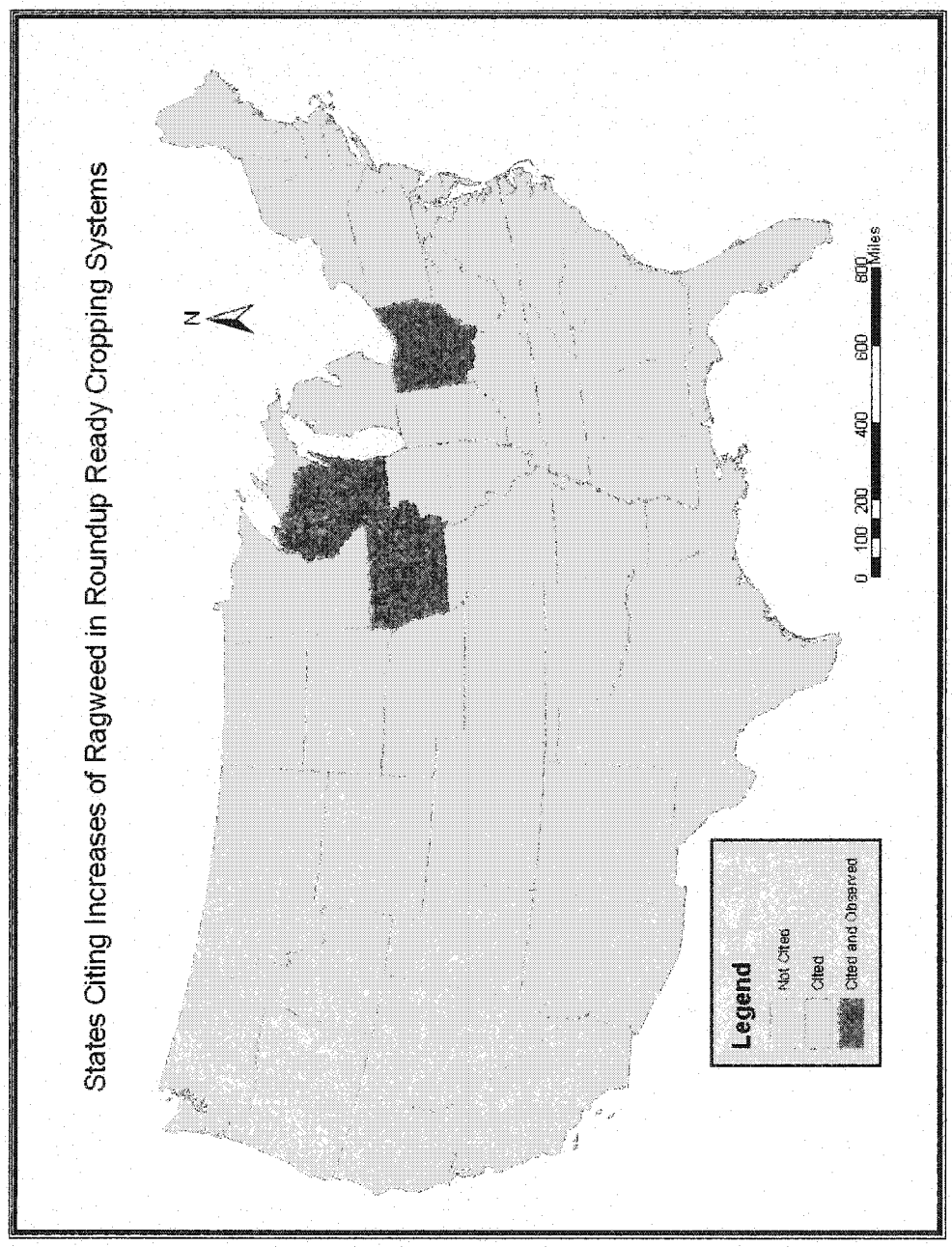

FIGURE 5.5, states reporting increases of ragweed (*Ambrosia spp.*) in Roundup Ready™ crop technology.

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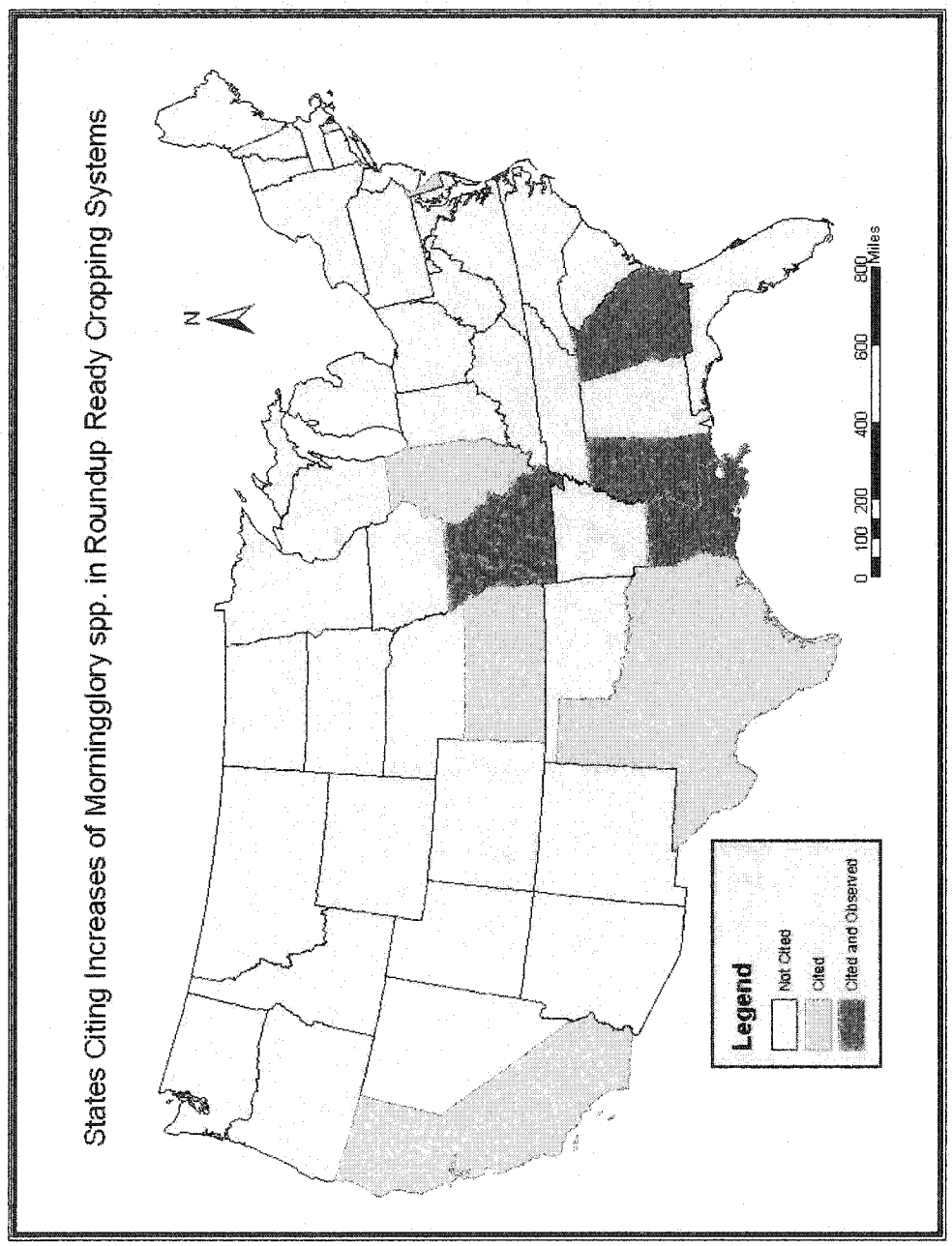

FIGURE 5.6, states reporting increases of morningglory spp. (*Ipomoea spp.*) in Roundup Ready™ crop technology.

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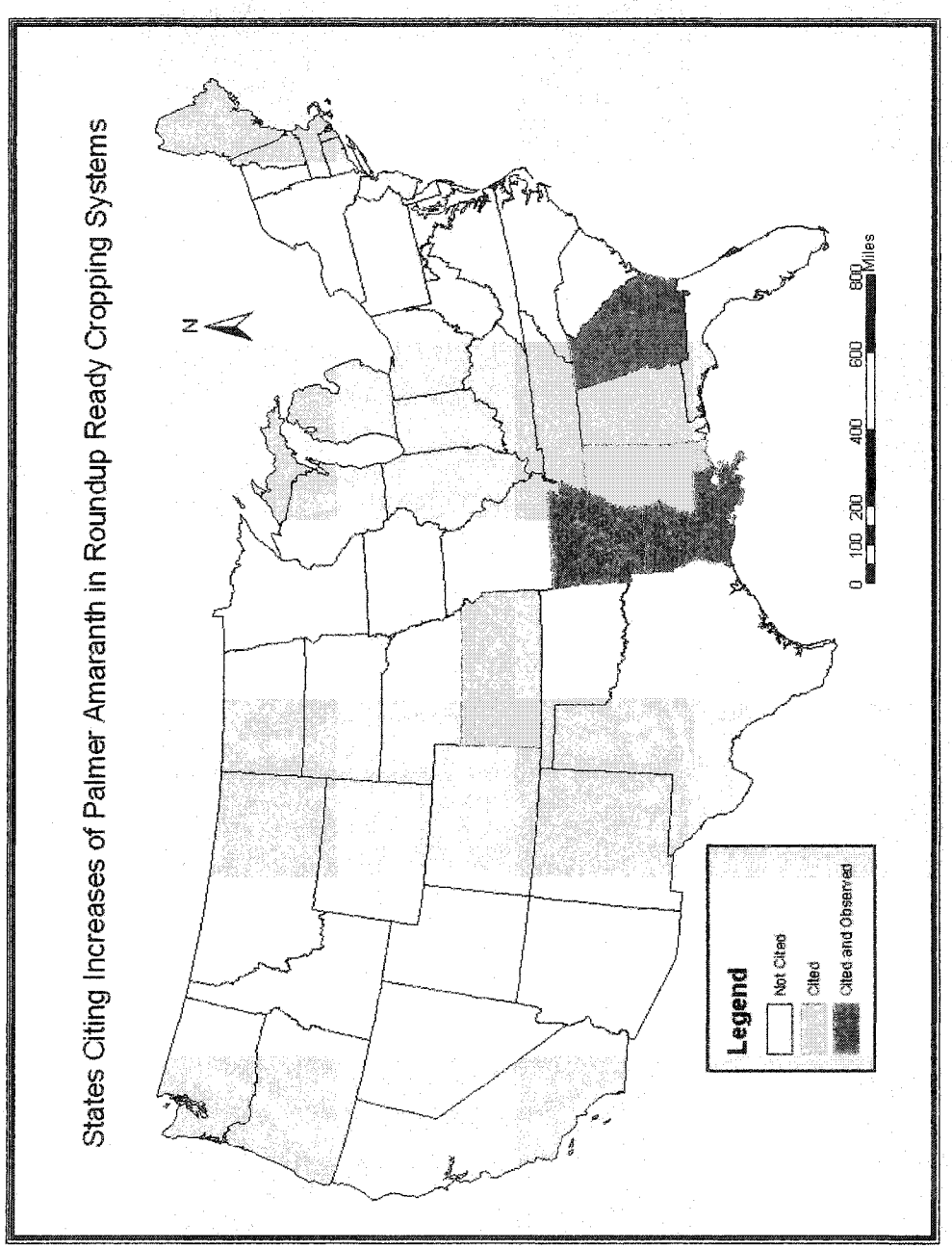

FIGURE 5.7, states reporting increases of palmer amaranth (*Amaranthus palmeri*) in Roundup Ready™ crop technology.

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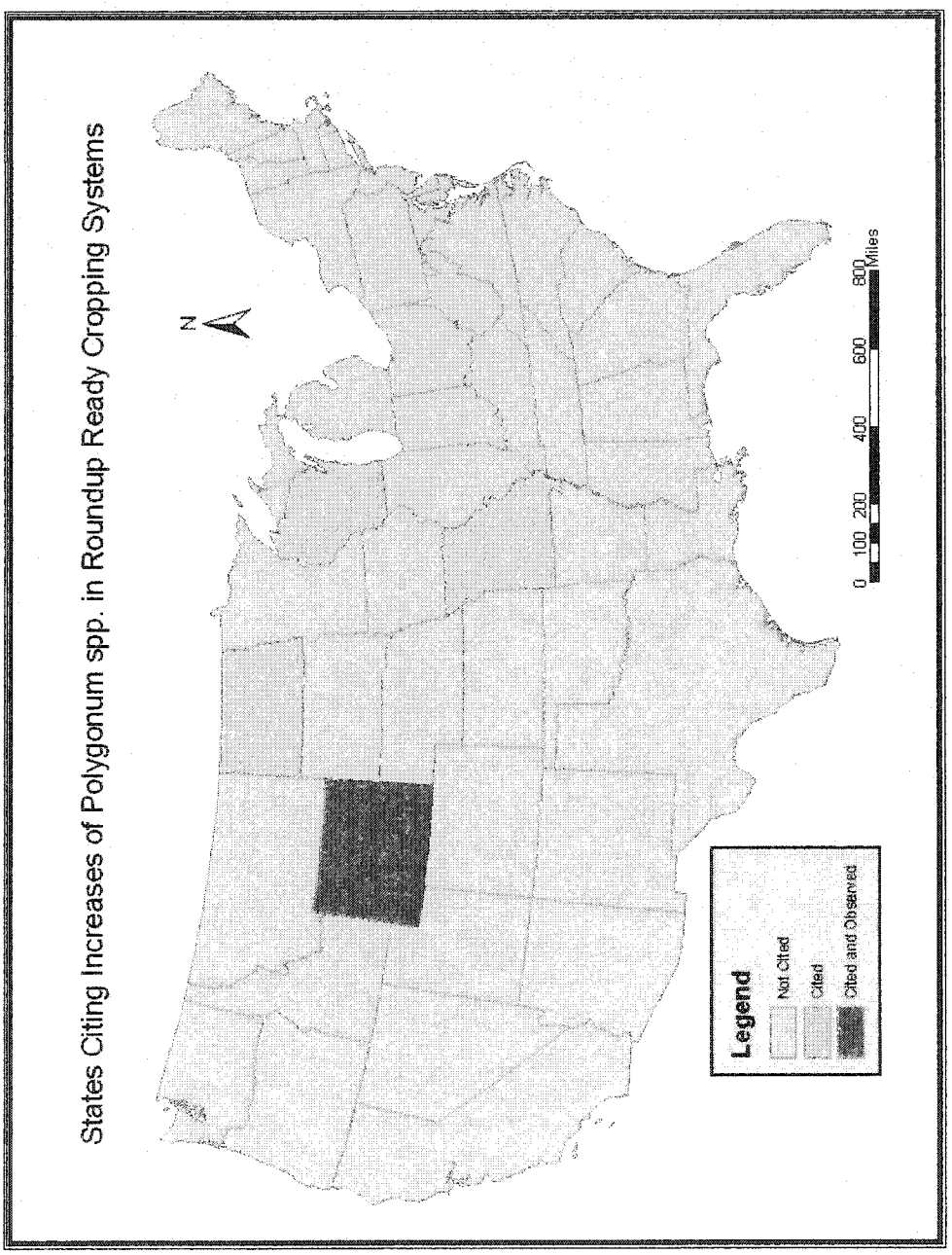

FIGURE 5.8, states reporting increases of *Polygonum spp.* in Roundup Ready™ crop technology.

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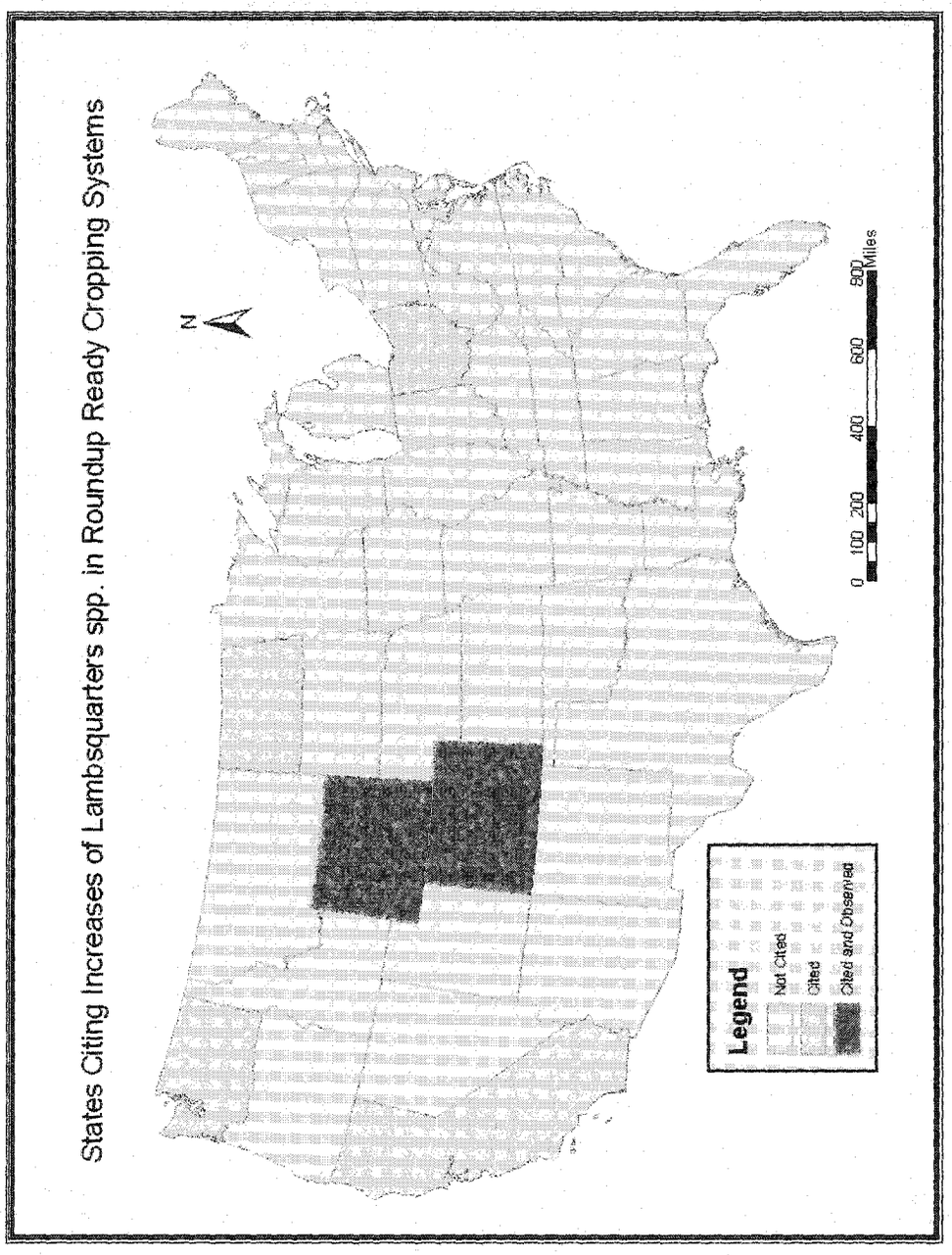

FIGURE 5.9, states reporting increases of common lambsquarters (*Chenopodium album*) in Roundup Ready™ crop technology.

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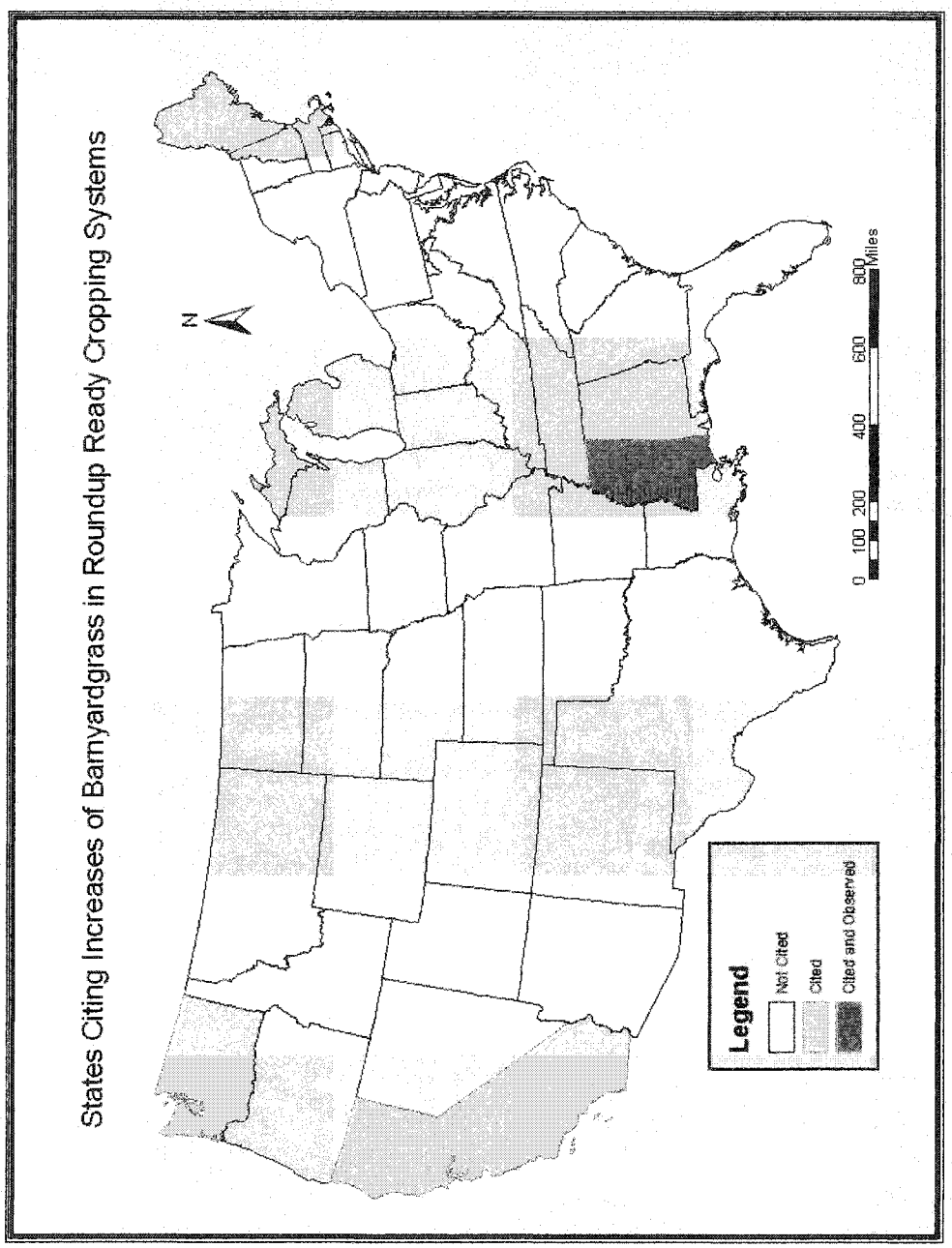

FIGURE 5.10, states reporting increases of barnyardgrass (*Echinochloa crus-galli*) in Roundup Ready™ crop technology.

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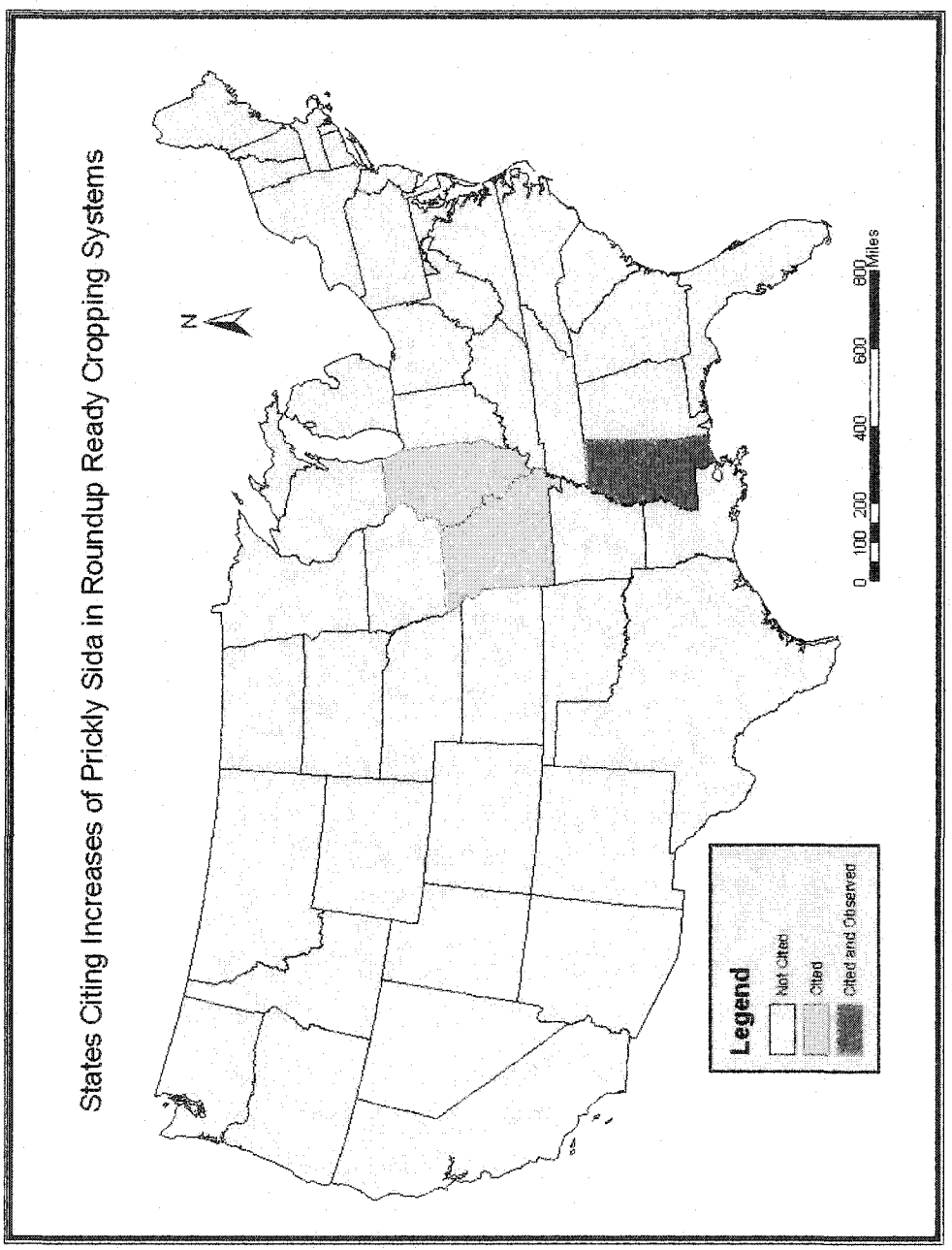

FIGURE 5.11, states reporting increases of prickly sida (*Sida spinosa*) in Roundup Ready™ crop technology.

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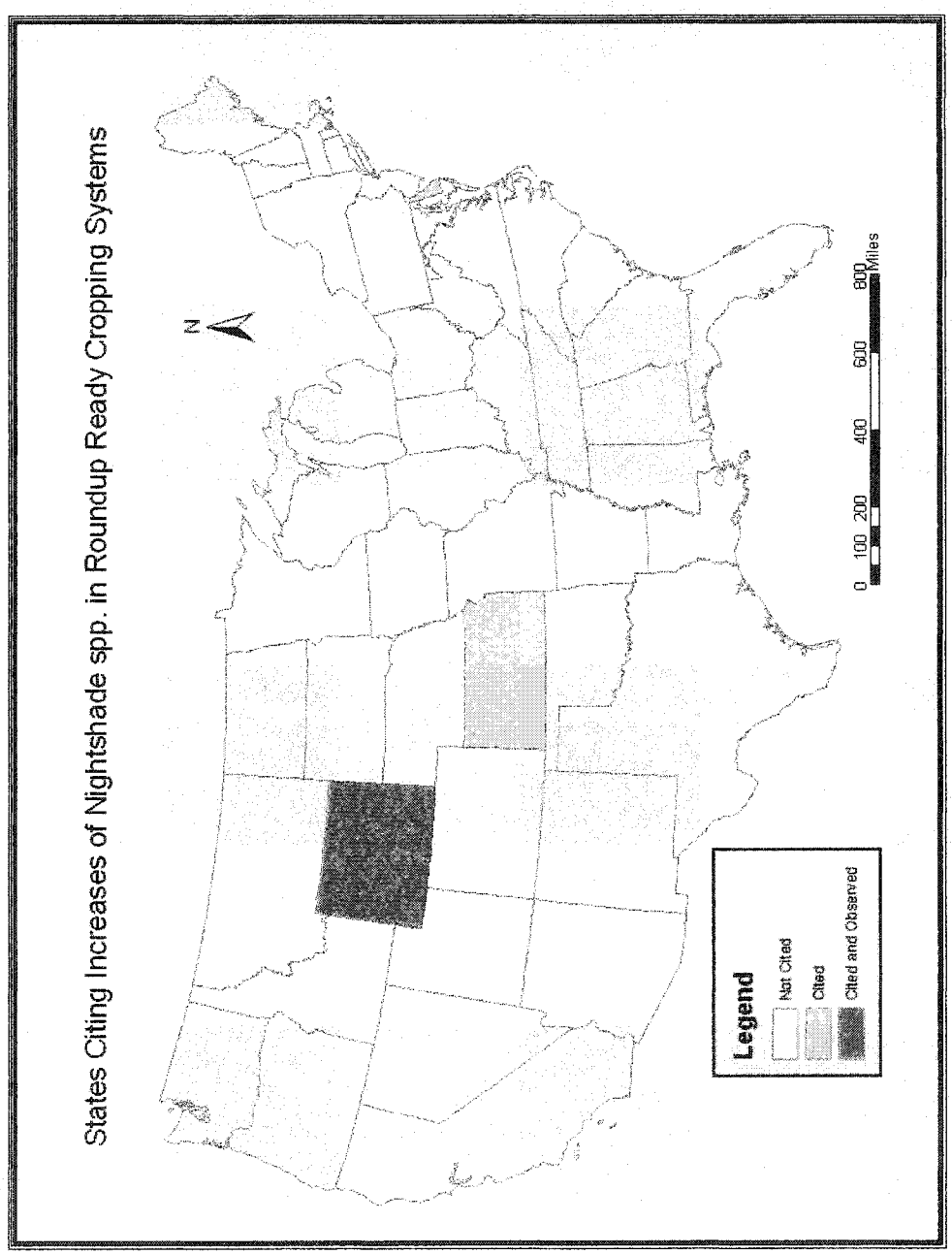

FIGURE 5.12, states reporting increases of nightshades (*Solanum spp.*) in Roundup Ready™ crop technology.

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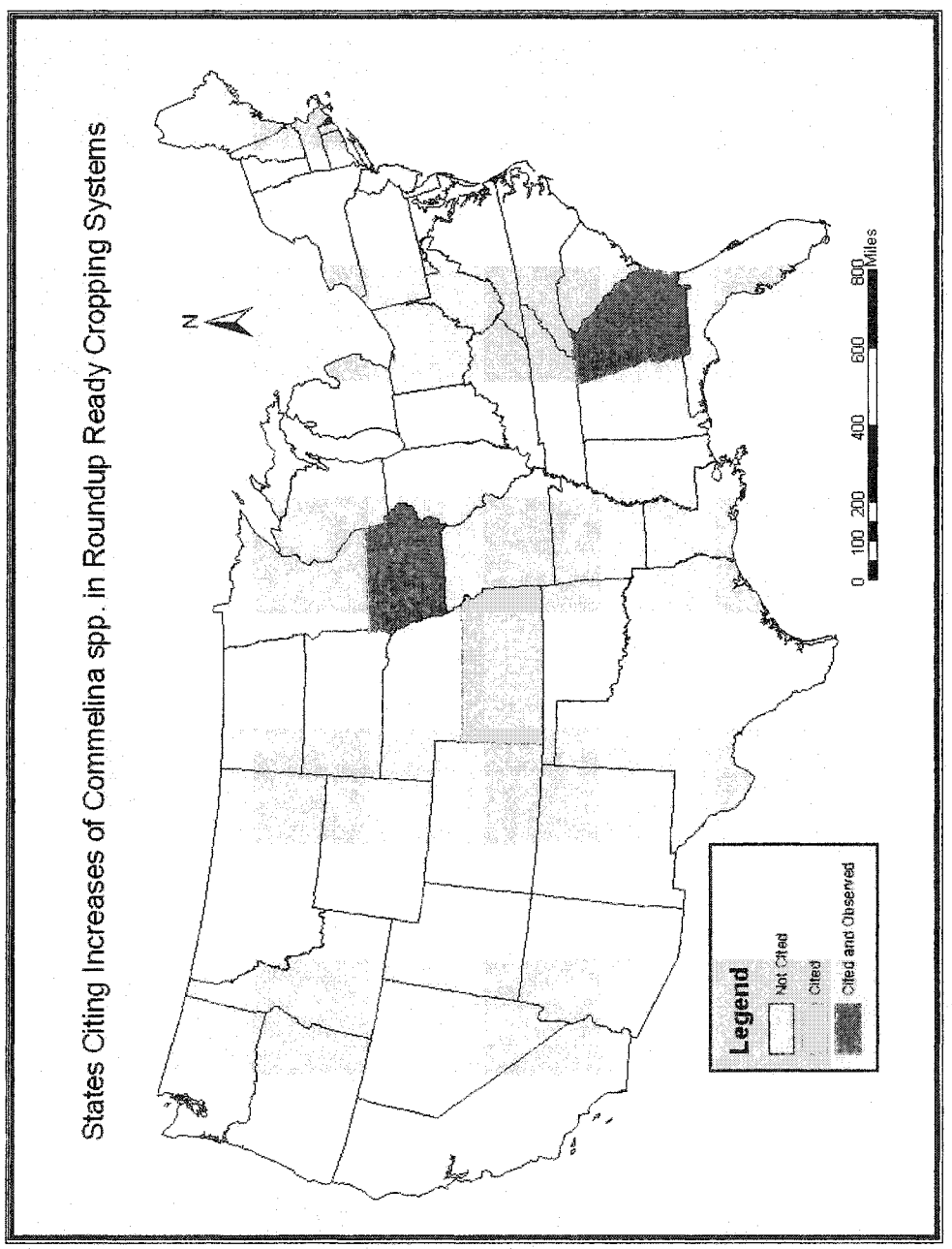

FIGURE 5.13, states reporting increases of *Commelina spp.* in Roundup Ready™ crop technology.

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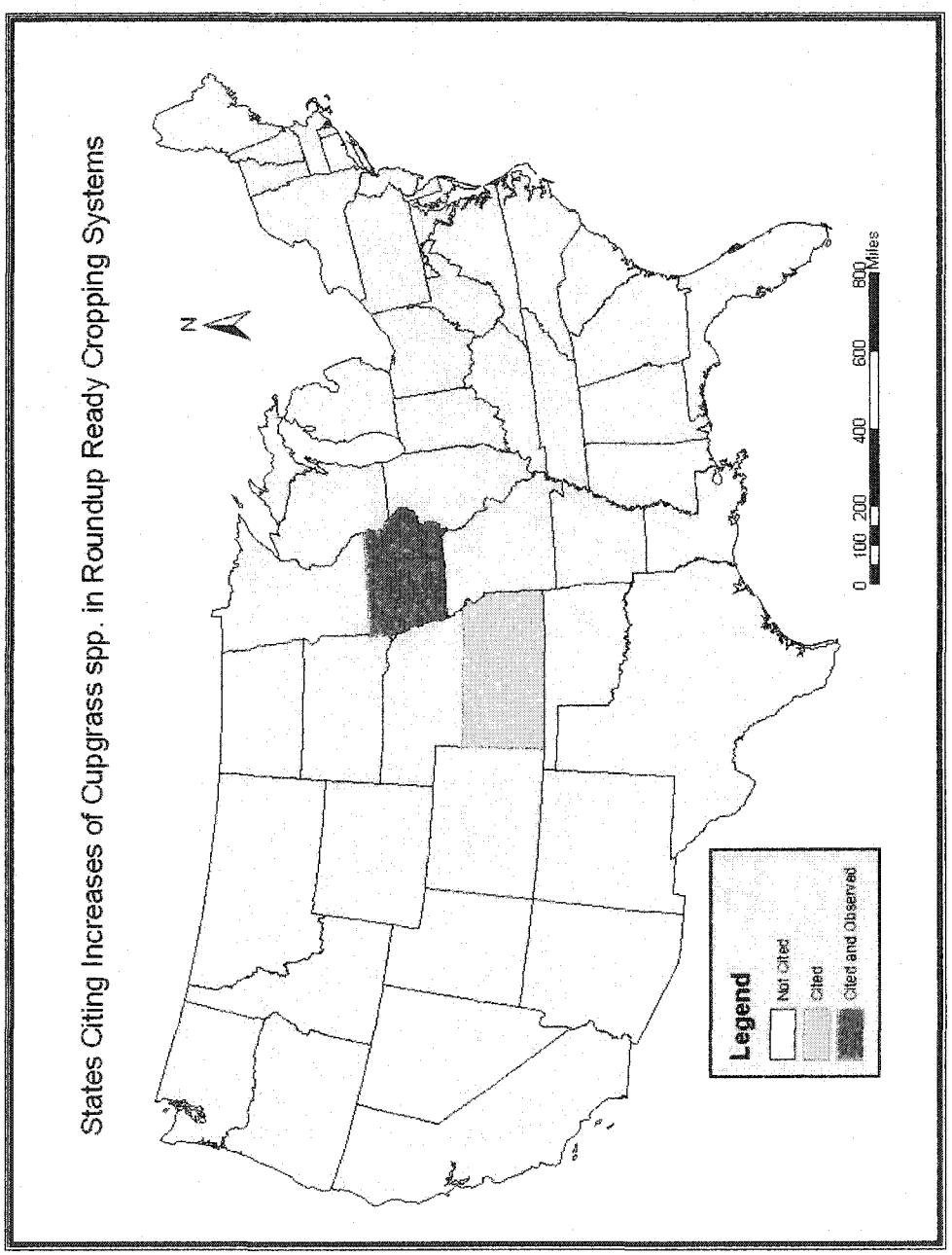

FIGURE 5.14, states reporting increases of cupgrass spp. (*Eriochloa spp.*) in Roundup Ready™ crop technology.

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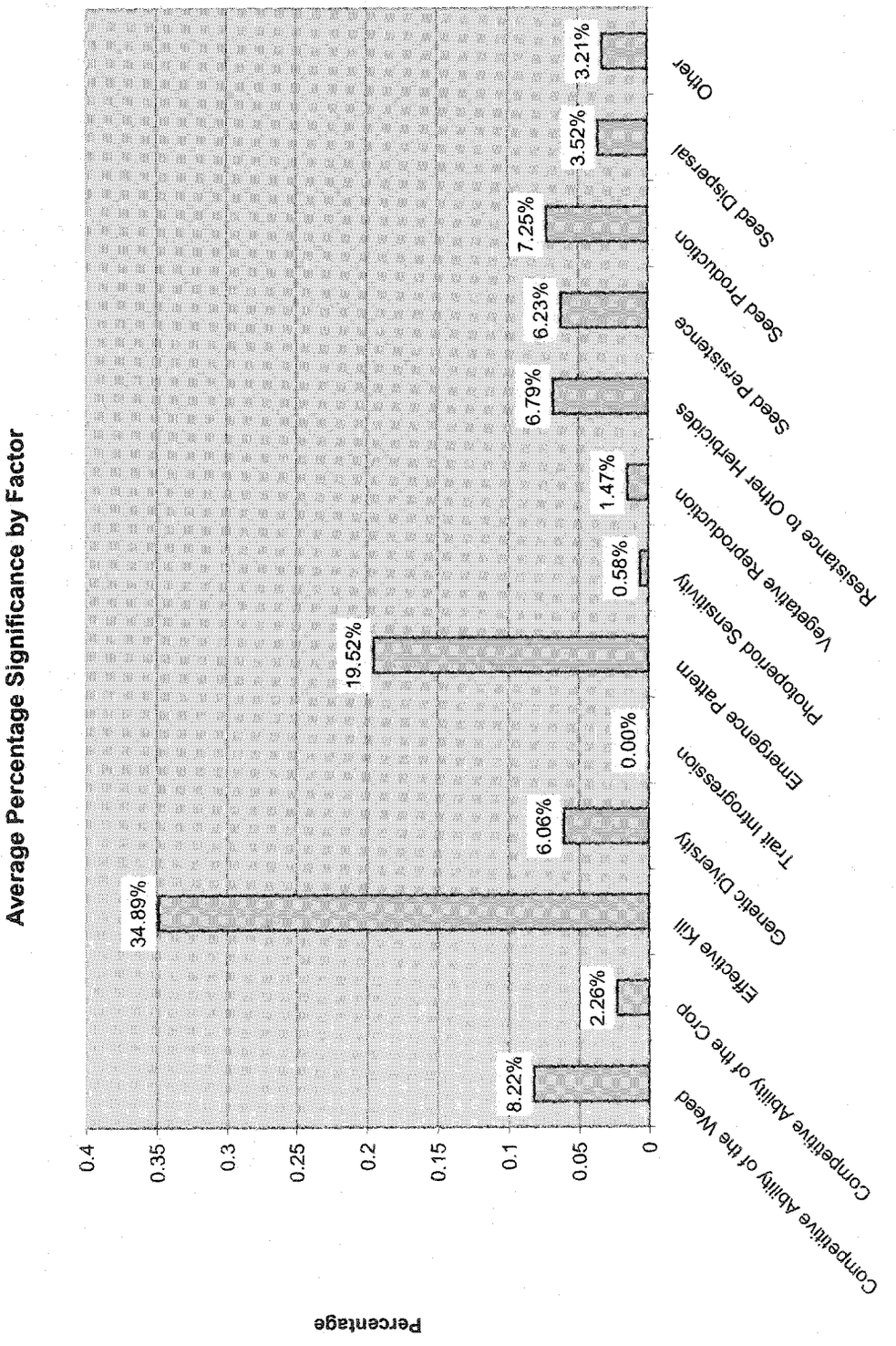

FIGURE 5.15, Average significance of each ecological factor for all weed shifts.

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Chapter 6.0
Weed Shifts in Roundup Ready™ Crops II: An Extensive Data Set

"I will go root away the noisome weeds that choke out the elements from wholesome flowers."

William Shakespeare
Richard III

The data of Miller (2004) is a multi-species agronomic weed shift study spanning five years. It is actually part of a large-scale study spanning four additional sites. It employs the use of glyphosate in conjunction with Roundup Ready™ crops and specifically attempts to ascertain whether increases in some weed species in such cropping systems can be best mitigated by an increase in the rate of glyphosate or by the supplementation of conventional herbicide treatments. It does this in the context of two crop rotations, continuous corn and corn in rotation with sugarbeets and wheat. The complexity of the experimental design combined with the magnitude of the resulting data makes the process of analysis nontrivial. In this study such an analysis is performed, and it contains three components. The first component is an effort to discern which combinations of cropping systems and herbicide treatment programs are associated with the highest populations or fastest growth rates of any given weed species. This section will show results from the Fort Collins site as well as two similar sites for five weed species of choice. The second analysis component focuses on differences in yield and makes a simple bioeconomic analysis of which crop rotation and treatment program

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would be the most favorable. The third analysis attempts to ascertain which weed species population increases are associated with the most significant decreases in crop yield. The study concludes with a section providing suggestions for further analysis.

6.1 Initial Dataset Description

The study of Miller (2004) is a five-year study taking place in the ARDEC facility located just north of Fort Collins, Colorado. The study was intended to monitor crop yields and densities of all weed species under a variety of crop rotation and treatment scenarios.

Two different crop rotation scenarios were utilized; they were a continuous corn scenario (CC) and a corn/soybeans rotation (CR) that also included wheat in its final rotational year. In general the herbicide treatment programs fell into two categories:

- A glyphosate-based herbicide approach
- A conventional herbicide approach

Two different glyphosate treatment programs were used. The first involved two separate treatments at the standard rate:

- Glyphosate 0.38 lb a.e./A

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- Glyphosate 0.38 lb a.e./A

where the first treatment was made near the start of the growing season, and the second was made a few weeks into the growing season. The second glyphosate treatment program also involved two such treatments, but at rates which were double that of the standard rate:

- Glyphosate 0.75 lb a.e./A
- Glyphosate 0.75 lb a.e./A

These two treatment programs were respectively referred to as the "glyphosate half-rate" (G(1/2)) and "glyphosate full rate" (G(Full)) treatment programs, and they were compared against a set of conventional herbicide treatment programs, which varied depending on the crop and rotation. In the case of continuous corn this conventional treatment program involved a single application of acetochlor and isoxaflutole:

- Acetochlor 1.75 lb a.i./A PRE + Isoxaflutole 0.06 lb a.i./A PRE

in every year except for every fourth year, where an additional application of diflufenzopyr and dicamba was added:

- Acetochlor 1.75 lb a.i./A PRE + Isoxaflutole 0.06 lb a.i./A PRE
- Diflufenzopyr + Dicamba 0.26 lb a.i./A POST

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For the Corn/Sugarbeets/Wheat rotation this conventional herbicide program involved three applications of tank mixtures involving phenmedipham, desmedipham, ethofumesate, and triflusulfuron:

- Phenmedipham + Desmedipham + Ethofumesate 0.33 lb a.i./A POST, Triflusulfuron 0.02 lb a.i./A POST, Clopyralid 0.09 lb a.i./A POST
- Phenmedipham + Desmedipham + Ethofumesate 0.33 lb a.i./A POST, Triflusulfuron 0.02 lb a.i./A POST, Clethodim 0.13 lb a.i./A POST
- Phenmedipham + Desmedipham + Ethofumesate 0.33 lb a.i./A POST

every year except the year for wheat, which utilized a single application of Starane and Sword:

- Starane / Sword

This treatment program was commonly referred to as the 'conventional' treatment program (Conv).

Finally, there was also a treatment program which was essentially a two-year rotation between the glyphosate full-rate and conventional treatment programs. In continuous corn (CC) the glyphosate treatments took place in odd years and the conventional treatments took place in even years, still with the supplementary dicamba

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treatment taking place in every fourth year. In the corn/soybeans/wheat rotation (CR) the glyphosate treatments also took place in odd years. In even years the same conventional treatments were utilized as before. This fourth treatment program was termed a 'rotational' treatment program, and in this analysis is given the shorthand (G/C) to signify the use of both glyphosate and conventional approaches.

Thus, an initial glance indicates this study to be a 2 × 4 factorial analysis involving two crop rotations:

1. Continuous corn (CC)
2. Corn in rotation (CR)

and four herbicide treatment approaches:

1. Glyphosate at the half-rate (G(1/2))
2. Glyphosate at the full-rate (G(Full))
3. Rotation between glyphosate and conventional (G/C)
4. Exclusively conventional with no glyphosate (Conv)

where the evaluation of treatment programs contains two important specific objectives. Since it is known from previous studies that some weed species do exhibit population increases in Roundup Ready™ cropping systems employing glyphosate treatments at standard rates, some question exists as to the best management response to such weed

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shifts. Is the best solution to simply double the rate of glyphosate or incorporate conventional treatment strategies? In addition, information is also desired on the potential risks associated with reducing the rate of glyphosate by half (G(1/2)) in regards to weed shifts. Such specific comparisons will be implicit foci in this analysis.

In each plot observations were made of crop yield, weed populations, and seed bank populations. Weed populations were measured for each plot at three times in the growing season, and, thus, temporally interspersed with the treatment programs as follows:

- FIRST WEED COUNT OBSERVATION
- Treatment #1
- SECOND WEED COUNT OBSERVATION

  (A few weeks after Trt #1)
- Treatment #2
- FINAL WEED COUNT OBSERVATION (End of growing season)

The weeds whose populations were measured in this study were:

ABUTH (Velvetleaf)

AMARE (Redroot pigweed)

CCHIN (Field sandbur)

CHEAL (Common lambsquarters)

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CIRAR (Canada thistle)

CONAR (Field bindweed)

DATST (Jimsonweed)

ECHCG (Barnyardgrass)

EPHDE (Toothed spurge)

HELAN (Common sunflower)

KCHSC (Kochia)

LACSE (Prickly lettuce)

MALNE (Common mallow)

PANMI (Wild-proso millet)

POLAV (Prostrate knotweed)

POLCO (Wild buckwheat)

POLPY (Pennsylvania smartweed)

POROL (Common purslane)

SASKR (Russian thistle)

SETXX (Foxtail spp.)

SOLNI (Black nightshade)

XANST (Common cocklebur)

Volunteer corn

where the appropriate Bayer codes have been included where appropriate.

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Each of the three seasonal weed population measurements involved fifteen quadrat observations spaced at regular spatial intervals within each plot. Seed bank populations were measured annually at the start of the growing season, and harvest data was, of course, measured at the end of the growing season.

6.2 Theoretical Development

Initially this investigation focuses on questions, each of which eventually manifests itself in one or more analytical methodologies with corresponding hypotheses. We begin with the first question.

Question 1

In what way can weed population dynamics be associated with different herbicidal treatments or crop rotations utilized in this study?

Question 2

Which cropping system and treatment program is most economically favorable?

Question 3

Which weed species have population dynamics that can be statistically associated with reductions in crop yield?

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Investigations into addressing the first question have involved a two-pronged approach, involving two separate hypotheses concerning the way in which weed population dynamics can be statistically detectible.

Hypothesis 1A

Different herbicidal treatment programs and crop rotations produce different dynamics in weed populations, and such differences are detectible as different average weed densities observed in conjunction with such long-term management decisions.

The above hypothesis may at first appear to be trivial and obvious, but the second hypothesis below indicates that alternate methods of detection may exist:

Hypothesis 1B

Different herbicidal treatments and crop rotations produce different dynamics in weed populations, and such differences are detectible in the form of a population trend over all years of data.

Thus, two methodologies exist for detecting the same phenomena. The first merely focuses on detecting statistically significant differences in average populations among different management strategies. The second attempts to pinpoint trends in population growth or decline.

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The second question focuses on differences in yield, and results in a second hypothesis, which is as follows:

Hypothesis 2

Differences in crop yields and herbicide treatment costs can be quantified to provide information on which combinations of crop rotation and herbicide treatment program are financially optimal.

This hypothesis provides a bioeconomic rubric for comparisons between the various treatments for optimal viability. This rubric can be defined via the following basic equation based on the analyses of section 2.4:

$$P = C_c Y - C_f - C_h - C_a - C_s$$

where P is total seasonal profits resulting from yield Y multiplied by crop price C_c. The second term C_f denotes all of the agronomic operational costs not directly related to weed control (purchased materials, fuel, equipment maintenance and depreciation, rental costs, labor, taxes, etc.), the third term C_h is the cost of the herbicide, the term C_a represents the cost of herbicide application, and the final term C_s represents the cost of seed. If it is assumed that for each crop rotation and treatment program operational and application costs will be similar, then for comparison purposes the calculation of profits can be reduced to the following:

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$$P' = C_c Y - C_h - C_s$$

Thus, advantageous yield differences within the same cropping system must be large enough to overcome any herbicide cost differences. Since differences in yield are found to have significant year dependencies, such an evaluation may be season-specific.

Lastly, question 3 results in a third hypothesis:

Hypothesis 3

Differences in crop yields are quantitatively relatable to differences in densities of one or more weed species according to the equation adapted from Spitters, Kropff, and de Groot (1989).

Hypothesis 3 is essentially an effort to connect these yield differences to differences in weed densities. We employ the following theoretical model adapted from Spitters, Kropff, and de Groot (1989):

$$\frac{1}{Y_{1,t}} = \mu + \eta_t + \sum_{i=2}^{n} \beta_i N_{i,t}$$

where weed densities, shown in the summation term, are said to affect reciprocal yield. This model formulation pulled directly out of the discussion in section 3.1. This model formulation is chosen primarily for its completely linear form on the right hand side,

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which provides for quick model selection processes. Note that the η_t term above allows for a difference in the maximum yield from year to year (Swinton et al., 1994), and some question exists as to which season observation timing at which each weed density $N_{i,t}$ should be taken. In the upcoming analysis, weed densities at each observational timing will be tested for such statistical correlation.

6.3 Experimental Design and Statistical Methods

6.3.1 Hypotheses 1A and 1B

Initially the following subscripts are defined:

i : Plant species ($i \in \{1,\ldots,m\}$), where the crop is referred to as species 1, and weed species take up subsequent i values.

j : Block, where $j \in \{1,\ldots,n\}$

r : Crop rotation, where $r \in \{1,\ldots,s\}$

k : Treatment program, where $k \in \{1,\ldots,p\}$

t : Crop season, where $t \in \{1,\ldots,v\}$

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q : Observational timing, where $q \in \{1,\ldots,r\}$

where the above subscripts apply to the following observed quantities:

N : Weed population

S : Seed bank population

Y : Yield per unit area

and effects from the following factors will be ascertained:

μ : Statistical grand mean

α_r : Effect of crop rotation r

γ_k : Effect of treatment program k

β_j : Effect of block j

η_t : Effect of environmental factors in year t

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δ_q : Effect of observational timing q

ε : Statistical error term

The basic design of the experiment was an RCB split-plot design (FIGURE 6.1) with a systematic sampling technique for each plot (FIGURE 6.2). The fact that it is a split-plot of two or more levels indicates that it is an 'experiment within an experiment', where crop rotation issues are addressed on the large scale, and treatment effects are assessed on the smaller scale. Usually with split-plot designs it can be anticipated that results will contain greater accuracy for the small-scale study (e.g., treatment effects) than the larger scale study (e.g., rotation effects). In addition, the presence of three different observations of weed populations suggests an additional repeated measures approach.

The conceptual framework of the study is shown in FIGURE 6.3, which shows in pictorial form the essential split-split-split plot structure of this experimental data, where the whole-plot factor is the crop, the first subplot factor is the treatment, the sub-subplot factor is the year, and the sub-sub-subplot factor is the observational timing. Considering also that the framework in FIGURE 6.1 applies to only a single site, it was decided that from an analytical perspective that the study should be broken into fifteen separate analyses, one for each combination of site and observational timing. Within each of these smaller studies the analysis follows a split-split plot structure with the whole-plot factor

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being the crop rotation, the first subplot factor being herbicide treatment, and the second subplot factor being year.

The latter subplot factor poses an additional degree of complexity in that it structural nesting is in time rather than in space, and, thus, the need for a repeated measures approach is indicated. For each sub-analysis the appropriate theoretical ANOVA table is displayed in TABLE 6.1, which is associated with the following model equation:

$$N_{rjktm} = \mu + \alpha_r + \beta_j + (\alpha\beta)_{rj} + \gamma_k + (\alpha\gamma)_{rk} + (\alpha\beta\gamma)_{rjk} + \eta_t + (\alpha\eta)_{rt} + (\gamma\eta)_{kt} + (\alpha\gamma\eta)_{rkt} + (\alpha\beta\gamma\eta)_{rjkt} + \varepsilon_{rjktl}$$

where the above process is now repeated for each combination of the five sites and three observational timings.

Implicit in any regression process involving the technique of ordinary least-squares is the assumption that the residuals described by the last term in the above equation be independently and identically distributed. When elements of repeated measures are considered, this assumption is lost. The methodology associated with a repeated measures analysis involves a regression technique that no longer makes use of a constant variance, but now makes use of, in this case, a 5 × 5 covariance matrix:

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$$\begin{bmatrix} \sigma_{11}^2 & \sigma_{12}^2 & \sigma_{13}^2 & \sigma_{14}^2 & \sigma_{15}^2 \\ \sigma_{21}^2 & \sigma_{22}^2 & \sigma_{23}^2 & \sigma_{24}^2 & \sigma_{25}^2 \\ \sigma_{31}^2 & \sigma_{32}^2 & \sigma_{33}^2 & \sigma_{34}^2 & \sigma_{35}^2 \\ \sigma_{41}^2 & \sigma_{42}^2 & \sigma_{43}^2 & \sigma_{44}^2 & \sigma_{45}^2 \\ \sigma_{51}^2 & \sigma_{52}^2 & \sigma_{53}^2 & \sigma_{54}^2 & \sigma_{55}^2 \end{bmatrix}$$

where the repeated measures analysis seeks to infer the general nature of this matrix as a part of the analysis. Generally the hypothesis structure of a repeated measures analysis proceeds as follows:

H_0: Compound symmetry

H_{a1}: Temporally autoregressive

H_{a2}: Unstructured covariance

where the term 'compound symmetry' refers to the absence of any complex covariance structure which would warrant the additional repeated measures analysis.

The first of the two alternate hypotheses are known as autoregressive, which theorizes the following structure to the covariance matrix:

$$\begin{bmatrix} \sigma^2 & \rho\sigma^2 & \rho^2\sigma^2 & \rho^3\sigma^2 & \rho^4\sigma^2 \\ \rho\sigma^2 & \sigma^2 & \rho\sigma^2 & \rho^2\sigma^2 & \rho^3\sigma^2 \\ \rho^2\sigma^2 & \rho\sigma^2 & \sigma^2 & \rho\sigma^2 & \rho^2\sigma^2 \\ \rho^3\sigma^2 & \rho^2\sigma^2 & \rho\sigma^2 & \sigma^2 & \rho\sigma^2 \\ \rho^4\sigma^2 & \rho^3\sigma^2 & \rho^2\sigma^2 & \rho\sigma^2 & \sigma^2 \end{bmatrix}$$

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Simply put, this involves a covariance structure involving only one additional parameter, ρ, which multiplicatively reduces the covariance a certain amount for every year of difference between the two observations. The second alternative hypothesis assumes no structure (i.e., in this case the addition of 24 more parameters) to the covariance matrix and for this analysis was thought to be too complex.

As is indicated by the above hypothesis structure, implicit in any repeated measures analysis is the detection of suitable evidence that such complex covariance structure is present, thus rejecting the null hypothesis that no such structure exists. In this study this is done by performing the analysis twice, once assuming compound symmetry and the other assuming an autoregressive covariance structure. Upon completing both analyses the "Log-likelihood" values from each of the studies are compared via a χ^2 analysis. A significant χ^2 value indicates sufficient evidence to reject the hypothesis of compound symmetry in favor of the autoregressive structure.

On an ecological note it should be pointed out that such an analysis into temporal covariance from year to year potentially provides insight into the strength of the ecological entity that causes weed populations to correlate from year to year – i.e., the strength of the seed bank.

In such an analysis the detection and assessment of fixed effects of treatment and crop rotation are desired, although it is reasonable to expect that significant year effects and interactions will also be detected, and it is granted that such interactions with year

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effects can mitigate the validity of the desired fixed effects of crop rotation and treatment. In the section to follow figures will be shown to illustrate such fixed effects, but similar adjacent plots will also show how such effects vary over the time period of the study. With the previous sentences in mind such a display is given in an effort to provide a kind of analytical compromise, showing the desired elements of detection but also additional information.

Such provides the analysis associated with hypothesis 1A. For hypothesis 1B the following equation was utilized:

$$N_{irklt} = \mu + \alpha_r + \gamma_k + [\eta + \alpha_r + \gamma_k + (\alpha\gamma)_{rk}]t + \varepsilon_{irklt}$$

where the term in brackets encloses effects on the desired slope in time *t*, thus indicating a trend. Note that effects from crop rotation and treatment program are allowed as well as an interaction between the two. In this analysis a backwards selection technique was used with the significance rejection threshold set at 0.05. In so doing the simplest regression equation for each weed species was acquired, the results of which will be displayed in the section to follow.

Again, it has been stated before that the data of Miller (2004) is actually part of a larger study spanning five experimental sites, each employing generally the same experimental objectives, design, and methods. FIGURE 6.4 shows the locations of these

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sites. Specifically in this analysis results will be presented for the irrigated sites – Fort Collins, Torrington, and Scottsbluff.

The analysis involved the use of the **proc mixed** utility in the SAS statistical package version 8e (SAS, 1999-2001) with multiple error terms and with differences among years for a given plot governed by an autoregressive residual covariance matrix. Successful satisfaction of model assumptions required the use of a logarithmic transformation prior to analysis, but the statistical results were presented with the averages of the raw data, so that unbiased estimates of average densities would be available.

FIGURE 6.5 illustrates an interesting peculiarity noticed during the data analysis. The presence of zeros in the dataset required a constant to be added to the data prior to the logarithmic transformation. The figure shows seven separate analyses on the same data, where all that differed was the constant added prior to performing the logarithmic transformation. Averages for the raw (untransformed) data are shown on the left, and on the right a graphical display of the transformed averages is shown for each of the seven analyses along with the transformation constant to the left and resulting LSD comparison letters shown to the right. This example was one of several that revealed that in some circumstances the statistical result was highly dependent on the constant added prior to transformation. This was determined to be due to different proportions of zeros among different treatments and/or crop rotations resulting in differential biases exerted by the logarithmic transformation among treatment and/or crop rotation means. This issue was

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resolved by performing the evaluation multiple times using multiple constant choices. Evaluations of which analysis to utilize were made based on the quality of the resulting residual plots as well as whether or not the statistical result contradicted the relative sizes of the raw data averages.

The results presented here focus on five weed species:

AMARE	Redroot pigweed	(*Amaranthus retroflexus*)
CHEAL	Common lambsquarters	(*Chenopodium album*)
KCHSC	Kochia	(*Kochia scoparia*)
POLCO	Wild buckwheat	(*Polygonum convolvulus*)
Grasses	Total grasses	

6.3.2 Hypothesis 2

For hypothesis 2 a variant of the full model was again utilized:

$$Y_{rjktl} = \mu + \alpha_r + \beta_j + (\alpha\beta)_{rj} + \gamma_k + (\alpha\gamma)_{rk} + (\alpha\beta\gamma)_{rjk} + \eta_t + (\alpha\eta)_{rt} + (\gamma\eta)_{kt} + (\alpha\gamma\eta)_{rkt} + (\alpha\beta\gamma\eta)_{rjkt} + \varepsilon_{rjktl}$$

where effects of crop rotation, treatment, and year were considered in the modeling of yields towards a determination of which management option was economically optimal. The above equation was used for each of the three crops – corn, sugarbeets, and wheat – although it was only used in its full form for corn. Since sugarbeets was only used in one

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of the two rotations and wheat for only one year in the same rotation, the equation for those crops was limited to the remaining factors of variance.

6.3.3 Hypothesis 3

For hypothesis 3 we recall the equation from the previous section:

$$\frac{1}{Y_{1,t}} = \mu + \eta_t + \sum_{i=2}^{n} \beta_i N_{i,t}$$

and make note of the fact that the right hand side of the equation has the potential of being lengthy, since the summation sign creates a separate term for each weed species. The techniques utilized for such model selection will be discussed more fully in that portion of the next section.

All statistical procedures involved the use of the **proc reg**, **proc glm**, and **proc mixed** procedures in the SAS software.

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6.4 Results and Discussion

6.4.1 Hypotheses 1A and 1B

First focusing on effects of crop rotation, FIGURE 6.6 shows average densities for early, mid-season, and late-season kochia for continuous corn (CC) and corn in rotation (CR). These are presented along with LSD difference letters denoting significant differences in such densities across crop rotations. Thus, in FIGURE 6.6 the results for Fort Collins show significantly lower densities in continuous corn for early, mid, and late-season populations. This is echoed to some extent at the other sites but not to a statistically significant extent. FIGURE 6.7 shows how these averages trend in time, where at Fort Collins a significantly higher trend is observed in the corn in rotation plots ($p < 0.01$). This significant difference in trend is echoed at Torrington only for mid-season populations ($p = 0.0309$) and at Scottsbluff only for early-season populations ($p < 0.0001$).

FIGURE 6.8 shows averages for wild buckwheat across the same crop rotations. Significantly lower populations were observed in the plots employing corn in rotation at both Torrington and Fort Collins. Such differences were not detected at Scottsbluff, but this may be simply due to extremely low populations at that site. FIGURE 6.9 shows that

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trend differences also exist across crop rotations at Fort Collins for early and mid-season populations ($p < 0.05$) and at Torrington for mid and late-season populations ($p < 0.001$).

Results similar to those of kochia are observed in FIGURES 6.10 and 6.11 for total grasses, where significant differences across rotation in early and late season populations at Fort Collins are observed in mid-season populations at Torrington. In addition, trend differences displayed in FIGURE 6.11 were detected at Fort Collins for all seasonal timings.

FIGURE 6.12 show averages of redroot pigweed across different treatment programs. Two of the three sites indicate superior control for the conventional treatment program (Conv) and the rotational treatment program (G/C). This is confirmed with the trend analysis results (not shown) which indicate significantly lower trends in the conventional treatment program versus the continuous high glyphosate treatment program, G(Full), detected in Fort Collins for late-season pigweed ($p = 0.0189$) and at Torrington for mid-season pigweed ($p = 0.0115$).

Some very significant findings were observed for averages of common lambsquarters across herbicide treatments. FIGURE 6.13 illustrates that in particular with mid-season populations, which do the most crop damage, significantly higher populations were observed at all three sites in the half-rate glyphosate, G(1/2), treatment program, indicating that this treatment program, though initially apparently desirable from a cost-savings standpoint, is a potentially problematic course of action in the longer

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term. This is confirmed in the trend analyses displayed in FIGURE 6.14, which shows significantly higher ($p = 0.0095$) upward trends in mid-season populations for the G(1/2) treatment versus the continuous full rate treatment, G(Full), at Scottsbluff, and the same for early ($p = 0.0123$) and mid-season ($p = 0.0053$) populations at Fort Collins. Interestingly, at Torrington significant upward trends of mid-season lambsquarters were detected for all treatments except the conventional treatment, suggesting that at that location even the full rate treatment warrants some further monitoring.

Results for kochia across herbicide treatments are displayed in FIGURES 6.15 and 6.16. At Torrington and Fort Collins significantly higher mid and late-season populations are observed in the conventional treatment versus the continuous glyphosate treatments, G(1/2) and G(Full). This is also confirmed with a significant trend difference at Fort Collins between the conventional and the G(Full) treatment for early ($p = 0.0080$) and mid-season ($p < 0.0001$) populations, as well as at Torrington for the late-season populations ($p < 0.0484$).

For late-season populations of wild buckwheat, FIGURE 6.17 shows results similar to that of common lambsquarters, where average populations at Torrington and Fort Collins are significantly higher for the half-rate glyphosate treatment, further underscoring this as an undesirable treatment option. At both sites this is confirmed with significant trend differences between the half-rate, G(1/2), and full-rate, G(Full), glyphosate treatments for all seasonal timings. At the Fort Collins site there is also some indication of similarly inferior performance of the conventional and rotational treatments

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for early and mid-season populations. This also appears in the form of significant trend differences between the conventional and full-rate glyphosate treatments for early (p = 0.0037) and mid-season (p = 0.0003) populations.

Lastly, for total grasses across herbicide treatments the least preferable performance was observed in the conventional treatment for mid and late-season populations at every site (FIGURE 6.19). This was confirmed at Fort Collins with a significant trend difference (FIGURE 6.20) in early-season populations between the conventional treatment and the continuous full-rate glyphosate treatment (p = 0.0307).

TABLES 6.2 and 6.3 attempt to summarize this information by categorizing weed species according to preferable options of control. TABLE 6.2 does this for crop rotation, also listing which sites support such findings. TABLE 6.3 does the same for herbicide treatment, showing options for best control and worst control. FIGURE 6.21 shows a cluster analysis that combines the information in TABLES 6.2 and 6.3 into a single forum. Potentially three different weed ecologies are observed. Pigweed and lambsquarters display a weed biology and ecology that suggest that they thrive best in the half-rate glyphosate treatment, with some indication of a "preference" for crop rotation. Kochia and grasses show a greater preference for crop rotation, but clearly indicate an opposing herbicidal "preference" for the conventional herbicides. Wild buckwheat thrives best in continuous corn under glyphosate. Of course, the choosing of best management options means choosing the opposite scenario for each "preference" described above.

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6.4.2 Hypothesis 2

Considering again the full model from before:

$$Y_{rjktl} = \mu + \alpha_r + \beta_j + (\alpha\beta)_{rj} + \gamma_k + (\alpha\gamma)_{rk} + (\alpha\beta\gamma)_{rjk} + \eta_t + (\alpha\eta)_{rt} + (\gamma\eta)_{kt} + (\alpha\gamma\eta)_{rkt} + (\alpha\beta\gamma\eta)_{rjkt} + \varepsilon_{rjktl}$$

a backwards selection technique was utilized in an effort to remove terms of undemonstrated significance. From the resulting model average harvest yields were acquired and statistically compared. The results for corn are shown in FIGURE 6.22 for each combination of crop rotation and treatment. It is immediately visible that the growing of corn in the context of a rotation with sugarbeets has a significant positive effect on corn yields in the half-rate glyphosate and conventional treatment programs. For the remaining treatment programs the observable positive difference between continuous corn and corn in rotation was of undemonstrated statistical significance. In addition, in continuous corn the use of the conventional treatment program was associated with significantly lower yields, apparently indicating crop injury by these conventional herbicides.

For sugarbeets the results are displayed in FIGURE 6.23, where the use of the conventional treatments was associated with significantly smaller yields.

Lastly, results for wheat are displayed in FIGURE 6.24, again showing significantly lower yields with the treatment programs involving conventional herbicides.

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TABLE 6.4 uses the results from FIGURES 6.22, 6.23, and 6.24 to calculate annual gross profits by multiplying yield by crop price, where harvest prices for corn, sugarbeets, and wheat were respectively set to $2.20/bu, $40.00/ton, and $3.00/bu. In addition, seeding costs were also subtracted at a rate of $26.00/acre for corn, $32.00/acre for sugar beets, and $10/acre for wheat. In addition, TABLE 6.5 shows herbicide treatment costs, which were calculated for each treatment program. Interestingly, a large difference was observed in the calculated differences in average annual herbicide treatment costs. Subtracting these treatment costs from the above gross profits resulted in the net profit comparison values shown in TABLE 6.6, where it becomes immediately apparent that the higher costs associated with the conventional herbicide treatments (in particular for the crop rotation) are not associated with economically advantageous increases in gross yield profits. The results indicate that the most economically advantageous solution would be to tend to gravitate away from the use of conventional herbicide chemistry as well as to gravitate towards a crop rotation of corn, sugar beets, and wheat over continuous corn.

6.4.3 Hypothesis 3

In the first section the dynamics of weed populations were assessed for different cropping systems and treatment programs. In the second section crop harvest data was investigated for discerning which scenario is indicated as most economically favorable. In this last section an attempt is made to connect this harvest data with weed population

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data in a fashion that suggests specific weed species as being the most influential in affecting crop yields. As was stated before, the following equation is utilized:

$$\frac{1}{Y_{1,t}} = \mu + \eta_t + \sum_{i=2}^{n} \beta_i N_{i,t}$$

where reciprocal yield data is regressed on weed population data. In addition, maximum yield (or minimum reciprocal yield μ) is allowed to vary from year to year via the parameter η_t.

Since the above regression is linear, the associated model selection procedures were quick and efficient, involving the `proc reg` statement in the SAS software. Four procedures were utilized for candidate model selection:

1. Forward selection, where the selection threshold was set to 0.05
2. Backward selection, where the selection threshold was set to 0.05
3. Stepwise selection, where both selection thresholds were set to 0.05
4. The selection of the four models with the highest adjusted R^2 value.

For each crop in the study, the above process was performed separately on weed densities in each of the three observational timings (TABLES 6.7 through 6.18). Thus, three candidate model charts appear for each crop. In each chart seven candidate models appear, with one column of data for each model. Each column shows the model's R^2 and

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adjusted R^2 value followed by the total number of parameters in the model and the number of those parameters that are of demonstrated significance at the 0.05 threshold level. Mallow's C_p and corrected AICC values follow (where such information was available), and the column concludes with a marking of which parameters existed in the model, where significant parameters are denoted with an 'XS' instead of merely an 'X'. Note that the abbreviations 'GRS', 'BLF', 'VLC' respectively denote total grasses, total broadleaves, and volunteer corn.

Presenting seven models in this format has two purposes, the first being to provide a convenient forum for comparative evaluation and the second being to observe general aspects of agreement among the candidate models. Looking first at TABLE 6.7, which shows the chart of models relating corn harvest data with weed densities measured at observation timing 1, it is observed that the first three of the above four methods generate the same model relating yield to year effects and densities of wild buckwheat, Russian thistle, and total grasses. The latter four models indicate significant associations with both total grasses, total broadleaves, and Russian thistle as well as significant year effects. Associations of undemonstrated significance are also indicated with redroot pigweed, Canada thistle, toothed spurge, wild sunflower, prostrate knotweed, and volunteer corn. In addition, the reader will notice the R^2 and adjusted R^2 values at the top of the chart. It is interesting to note that year effects and weed densities observed prior to any control efforts can explain up to 73% of the variation in corn harvest levels!

The models in each chart were compared according to three general criteria:

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1. Adjusted R^2 levels, where a higher value was considered favorable,

2. Number of significant parameters, where a higher number was considered favorable, and

3. Proportion of total parameters which were significant, where a higher proportion was considered favorable,

where the criteria is listed in order of priority.

For the combination of corn and early-season weed populations, TABLE 6.7 shows that the above priority rubric is reflected in the selection made from the first chart, which is Model 5, having the largest adjusted R^2 value as well as the largest number of significant parameters (although the lowest proportion of significant parameters).

Switching to the TABLE 6.8 the focus is shifted to weed populations observed in mid-season. A preponderance is observed for year effects as well as strong associations with densities of Canada thistle, jimsonweed, barnyardgrass, wild buckwheat, Pennsylvania smartweed, as well as total grasses and total broadleaves. Model 6 is discerned as most superior for its high adjusted R^2 as well as total number and high proportion of significant parameters.

In TABLE 6.9, which shows results for late-season weed densities, a strong dichotomy in candidate models is observed. Virtually all models show significant year

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effects as well as strong associations with wild sunflower, black nightshade, and common cocklebur. The latter four models, however, also indicate strong associations with wild proso millet, wild buckwheat, and common purslane as well as additional associations with Canada thistle, prickly lettuce, common mallow, and volunteer corn. Model 5 is chosen for its high adjusted R^2 as well as its high number of significant parameters.

TABLE 6.10 shows the strongest models extracted from the three previous candidate model tables. With the passage of time in the growing season, more variability in the harvest densities is explained (although the R^2 value suffers a curious dip mid-season). In addition, the explanation of such variability becomes more specific late-season, moving from the general 'total grasses' and 'total broadleaf' categories to specific weeds, and a larger number of specific weed species are observed as having statistically significant associations.

TABLE 6.11 shows results for sugarbeets and early-season weed populations. Presumably since sugarbeets were only grown in 1999 and 2001, year effects are less pronounced in most of the three candidate model charts for this crop. Here for early-season weed densities, model results appear to collectively point to jimsonweed, toothed spurge, wild sunflower, and kochia as having significant associations. Model 2 is strongly considered for its high number and proportion of significant parameters, but model 5 provides a much higher adjusted R^2 at the cost of only one significant parameter.

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For mid-season observations, TABLE 6.12 shows that year effects for the moment become more significant, and the weed species associations appear to become more focused. Strong associations are observed with common lambsquarters, Canada thistle, kochia, Pennsylvania smartweed, and total grasses. Model 5 is again chosen for its high adjusted R^2 and its high number of significant parameters. In addition, the same temporary decrease in the overall R^2 and adjusted R^2 values previously observed mid-season in corn (TABLE 6.8) is observed again here for sugarbeets.

For late-season weed observations, TABLE 6.13 illustrates that year effects fade away, and the species of strong association shift to redroot pigweed, common lambsquarters, toothed spurge, and total grasses. Again, model 5 is chosen for similar reasons.

TABLE 6.14 shows that common lambsquarters, Canada thistle, jimsonweed, toothed spurge, kochia, and total grasses appear to have strong associative connections with sugarbeet harvest.

Since wheat was only grown in the 2002 season, no year effects are visible here or in any of the other candidate model charts for this crop. The results for early-season weed densities, shown in TABLE 6.15, show strong collective indications of association with velvetleaf, redroot pigweed, wild sunflower, black nightshade, volunteer corn, and total grasses. In addition, the observation was previously made for corn that 73% of the harvest variability was successfully explained by year effects and weed densities

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observed prior to control practices. Here a similar observation is made, where as much as 96% of the total harvest variability is successfully explained by weed densities observed prior to any control efforts in 2002. Again, model 5 is chosen for a strong adjusted R^2 value and number of significant parameters.

For mid-season weed observations, TABLE 6.16 shows strong collective indications of associations with redroot pigweed, toothed spurge, wild sunflower, kochia, common cocklebur, and total broadleaf species. Model 2 (also seen as model 8) is chosen for its large number and proportion of significant parameters and reasonably high adjusted R^2 value. In addition, the now familiar mid-season decrease in the R^2 values is again observed here for wheat.

TABLE 6.17 shows that for late-season weed observations the associations again appear to become more focused on specific species. Here again the species are redroot pigweed, jimsonweed, barnyardgrass, toothed spurge, wild sunflower, kochia, wild buckwheat, and common cocklebur. Here model 7 is chosen for its high number and proportion of significant parameters and high adjusted R^2 value.

TABLE 6.18 shows all observational timings for weed density influences on wheat harvest, showing strong associations with velvetleaf, redroot pigweed, toothed spurge, wild sunflower, kochia, wild buckwheat, black nightshade, common cocklebur, and total grasses appear to prevail throughout most of the season.

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An important point should be made that the Hypothesis 3 model formulation allows for both synergistic and antagonistic interactions among plant species. Such interactions appear respectively as negative and positive β_i coefficients. This point attains specific relevancy here in that in virtually all of the models throughout this section at least some of the coefficients were negative, implying a synergistic interaction with the crop. It is at this point, however, that one must be reminded that correlation does not imply causation. The above charts describe associations, not interactions. With this in mind, such associations could involve causal interactions that are multitudinous and complex. For example, a significant negative association of a crop's reciprocal yield with a population density of a given weed species could be caused by that species' ability to successfully compete against other weed species that have direct antagonistic impacts on crop yield. One must be exceptionally careful, therefore, at interpreting these results. The species listed as significant are not necessarily those species providing the most robust inhibition of crop yield. Rather, they are the species whose densities serve as the best indicators of crop yield. Full ANOVA tables for each of the final models are displayed in Appendix C.

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6.5 Conclusions

One of the central questions governing this present study centered around potential risks of reducing the rate of glyphosate by half in agronomic applications. Results from this study indicate two weed species – common lambsquarters (*Chenopodium album*) and wild buckwheat (*Polygonum convolvulus*) – whose population dynamics and response to glyphosate make them strong potential risks in such a treatment program.

In addition, it is also of interest that when a comparison is made between the continuous full-rate glyphosate treatment program (G(Full)) and the rotation treatment program (G/C), no statistically significant difference is observed between these two programs in relation to mid-season populations of the above two species. This indicates that any benefit gained in rotating standard glyphosate chemistry in with herbicides employing other modes of action is undemonstrated, and although from a large-scale tolerance standpoint the importance of the inclusion of other herbicidal modes of action is understood, any direct impact on weed shifts cannot be immediately inferred here.

This latter point is of great significance considering the high herbicidal costs indicated in TABLE 6.5 for the treatments employing conventional chemistry. From the standpoint of net profit based upon the information provided, the optimal choice is to employ a standard glyphosate treatment program with corn in rotation.

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Lastly, from the analysis associated with hypothesis 3, although dependencies on specific weed species were highly variable, it is of grand interest that in each instance a very large portion of the variability in yield could be explained by variations in weed populations, and that separate influences of multiple species could be detected as statistically significant. This has important implications with respect to the upcoming development of the WISDEM model in chapters 7 and 8.

6.6 Suggestions for Further Analysis

The following questions and hypotheses provide suggestions for additional study:

6.6.1 Question 1

In what way can weed population dynamics be predicted in upcoming years based on management strategies, crop rotations, populations of other species, crop yields, or other phenomena?

FIGURE 6.25 shows a very simplistic fundamental model of weed population dynamics displayed in picture form, where the following demographic parameters are herein defined:

α_i : Proportion of seed bank emerging in a given season for species i

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ϕ_i : Per-plant fecundity for species *i*

$\sigma_{o,i}$: Seed rain overwintering survival for species *i*

$\sigma_{s,i}$: Annual seed bank survival rate for species *i*

and the following parameter is defined for management practices:

ε_i : Control efficacy of present crop and treatment program on species *i*

and for the moment all demographic parameters and control efficacies are considered constant. The above would be associated with the following equations for weed population dynamics:

$$N_{i,t} = \varepsilon_i \alpha_i S_{i,t} \qquad S_{i,t+1} = \sigma_o \phi_i N_{i,t} + (1-\alpha_i)\sigma_s S_{i,t}$$

These equations can be combined in two ways. For a representation of seed bank dynamics, the combination is as follows:

$$S_{i,t+1} = \sigma_o \phi_i \varepsilon_i \alpha_i S_{i,t} + (1-\alpha_i)\sigma_s S_{i,t} = \left[(1-\alpha_i)\sigma_s + \sigma_o \phi_i \varepsilon_i \alpha_i\right] S_{i,t}$$

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This indicates that linear regressions could be made on the annual growth rate of the seed bank population:

$$\frac{S_{i,t+1}}{S_{i,t}} = (1-\alpha_i)\sigma_s + \sigma_o\phi_i\varepsilon_i\alpha_i$$

where current theory suggests that the first term on the right hand side (controlled by emergence proportion and annual seed bank survival) would be relatively constant, and the second term (controlled by control efficacy, plant fecundity, and overwintering seed survival) would be relatively variable. Essentially the first term deals with matters of seed bank survival, and the second term deals with matters of weed management. Thus, linear regressions of the annual seed bank growth rate on effects of crop rotation, treatment program, and populations of other species would not only be fruitful in and of themselves, but they would also yield an intercept term which may provide insight into internal seed bank dynamics.

For a representation of weed population dynamics the combination becomes more complex:

$$N_{i,t+1} = \varepsilon_i\alpha_i\{\sigma_o\phi_i N_{i,t} + (1-\alpha_i)\sigma_s S_{i,t}\} = \varepsilon_i\alpha_i\sigma_o\phi_i N_{i,t} + \varepsilon_i\alpha_i(1-\alpha_i)\sigma_s S_{i,t}$$

Further combination results in:

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$$N_{i,t+1} = \varepsilon_i \alpha_i \sigma_o \phi_i N_{i,t} + \varepsilon_i \alpha_i (1-\alpha_i) \sigma_s \left[\sigma_o \phi_i N_{i,t-1} + (1-\alpha_i) \sigma_s S_{i,t-1} \right]$$

$$N_{i,t+1} = \varepsilon_i \alpha_i \sigma_o \phi_i N_{i,t} + \varepsilon_i \alpha_i (1-\alpha_i) \sigma_s \sigma_o \phi_i N_{i,t-1} + \varepsilon_i \alpha_i (1-\alpha_i)^2 \sigma_s^2 S_{i,t-1}$$

$$N_{i,t+1} = \varepsilon_i \alpha_i \sigma_o \phi_i N_{i,t} + \varepsilon_i \alpha_i (1-\alpha_i) \sigma_s \sigma_o \phi_i N_{i,t-1} + \varepsilon_i \alpha_i (1-\alpha_i)^2 \sigma_s^2 \left[\sigma_o \phi_i N_{i,t-2} + (1-\alpha_i) \sigma_s S_{i,t-2} \right]$$

$$N_{i,t+1} = \varepsilon_i \alpha_i \sigma_o \phi_i N_{i,t} + \varepsilon_i \alpha_i (1-\alpha_i) \sigma_s \sigma_o \phi_i N_{i,t-1} + \varepsilon_i \alpha_i (1-\alpha_i)^2 \sigma_s^2 \sigma_o \phi_i N_{i,t-2} + \varepsilon_i \alpha_i (1-\alpha_i)^3 \sigma_s^3 S_{i,t-2}$$

This suggests a (theoretically) infinite series of weed densities from previous years in the total representation of weed densities for the present year:

$$N_{i,t} = \varepsilon_i \alpha_i \sigma_o \phi_i \sum_{j=0}^{\infty} (1-\alpha_i)^j \sigma_s^j N_{i,t-j}$$

This provides some fundamental insight. In years where all demographic and managerial process have quantitatively identical effects, the weed population within a given year should be linearly correlated with all previous years, with the coefficient of correlation decreasing exponentially with the number of years hence.

Of course, the above is not the case, but the theory gives insight into methods of data analysis. A basic linear regression format is indicated for relating weed populations in a given year to the same in previous years.

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It also becomes clear that the presence of a seed bank makes potentially every previous year's weed population a predictive factor in the population of the present year. Thus, for practicality an artificial threshold must be set beyond which effects on the weed populations of the present year are considered negligible. It is probable that such a threshold may also be implicitly defined by the data analysis as the point at which effects drop below what is accepted as statistical significance.

Lastly, since managerial practices and crop rotations have the potential of affecting both the herbicidal efficacy ε as well as fecundity ϕ, then all of the regression terms are potentially affected thus.

For an example where this threshold is set to three years, the equation is as follows:

$$N_{i,t+1} = \varepsilon_i \alpha_i \sigma_o \phi_i N_{i,t} + \varepsilon_i \alpha_i (1-\alpha_i) \sigma_s \sigma_o \phi_i N_{i,t-1} + \varepsilon_i \alpha_i (1-\alpha_i)^2 \sigma_s^2 \sigma_o \phi_i N_{i,t-2}$$

and, if the assumption is lifted that herbicidal efficacy, fecundity, and overwintering survival are constant from year to year, the equation becomes:

$$N_{i,t+1} = \varepsilon_{i,t+1} \alpha_i \sigma_{o,t} \phi_{i,t} N_{i,t} + \varepsilon_{i,t+1} \alpha_i (1-\alpha_i) \sigma_s \sigma_{o,t-1} \phi_{i,t-1} N_{i,t-1} + \varepsilon_{i,t+1} \alpha_i (1-\alpha_i)^2 \sigma_s^2 \sigma_{o,t-2} \phi_{i,t-2} N_{i,t-2}$$

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Further, if dependencies on crop and treatment programs are now properly assumed for herbicidal efficacy, fecundity, and overwintering survival:

$$\varepsilon_{i,t} = f(\chi,\gamma)_{i,t} \qquad \phi_{i,t} = f(\chi,\gamma)_{i,t} \qquad \sigma_{o,i,t} = f(\chi,\gamma)_{i,t}$$

then several interactions are implied, all of them involving present year crop and treatment programs with crop and treatment programs from previous years:

$$N_{i,t+1} = \varepsilon_{i,t+1}(\chi,\gamma)\alpha_i\sigma_{o,t}\phi_{i,t}(\chi,\gamma)N_{i,t} + \varepsilon_{i,t+1}(\chi,\gamma)\alpha_i(1-\alpha_i)\sigma_s\sigma_{o,t-1}(\chi,\gamma)\phi_{i,t-1}(\chi,\gamma)N_{i,t-1} + \varepsilon_{i,t+1}(\chi,\gamma)\alpha_i(1-\alpha_i)^2\sigma_s^2\sigma_{o,t-2}(\chi,\gamma)\phi_{i,t-2}(\chi,\gamma)N_{i,t-2}$$

Thus, present theory suggests the following:

1. Linear regressions involving weed populations and the statistical parameters shown at the end of the previous section appear to be appropriate and show good promise for successful insight.
2. Linear regressions involving weed seed bank populations and the same statistical parameters also appear to be appropriate and show the same good promise.
3. Regressions involving weed seed bank populations best involve using annual seed bank growth rates as the dependent variable and effects from the interim growing season as independent variables.

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4. Regressions involving weed populations may need to involve effects from multiple years and multiple interaction terms. Theory implies that most such significant interaction terms will involve effects from the present year.

6.6.2 Question 2

How does one effectively represent the dynamics of weed emergence patterns within a given year?

Weed emergence patterns have in the past been effectively represented by some authors in terms of environmental conditions, and by others in terms of weed management events. Based upon this information, it appears most appropriate to relate weed densities at various times in the growing season to preceding control events in an earlier time period in the growing season.

This model is displayed in FIGURE 6.26, and implicitly defines three quantities that in the presence of control events can only be inferred indirectly. They are the first cohort – consisting of weeds that emerge prior to the first seasonal observation, the second cohort – consisting of weeds that emerge between the first and second seasonal observations, and the third cohort – consisting of weeds that emerge between the second and third observations.

The analyses are as follows:

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$$N_{ijklz,t,1} = \mu_i + \eta_{it} + \chi_{ij} + \gamma_{ik} + \beta_{il} + \varepsilon_{ijklz,t,1}$$

$$N_{ijklz,t,2} = \mu_i + \eta_{it} + \chi_{ij} + \gamma_{ik} + \beta_{il} + \left(\mu_i + \eta_{it} + \chi_{ij} + \gamma_{ik} + \beta_{il}\right)N_{ijkl,t,1} + \varepsilon_{ijklz,t,2}$$

$$N_{ijklz,t,3} = \mu_i + \eta_{it} + \chi_{ij} + \gamma_{ik} + \beta_{il} + \left(\mu_i + \eta_{it} + \chi_{ij} + \gamma_{ik} + \beta_{il}\right)N_{ijkl,t,2} + \varepsilon_{ijklz,t,3}$$

where we attempt to detect effects of crop rotation and treatment program on intraseasonal weed population dynamics. Such has been detected by previous authors (Stahl et al., 1999), and the present study may indicate specific additional examples.

6.6.3 Question 3

Can crop yields be predicted based upon weed densities according to other existing models in the literature?

The prediction of crop yields can be compared against the following theoretical model adapted from Cousens (1985):

$$Y_{1,t} = \left(\mu + \eta_t + \beta_j\right)\left(1 - \frac{\sum_{q=2}^{n} A_q \kappa_q N_{q,t}}{n_{50,1} + \sum_{q=2}^{n} \kappa_q N_{q,t}}\right)$$

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where the above analysis allows for a difference in the maximum yield from year to year (Swinton et al., 1994) as well as block to block, and weed densities are total densities measured at harvest.

6.6.4 Question 4

To what extent can significant dependencies of weed populations on similar populations in spatially adjacent plots be detected?

The map in FIGURE 6.27 shows an example of the fact that weed densities display some degree of spatial autocorrelation. This degree of spatial autocorrelation can be assessed by calculating Moran's I or Geary's C for the weed population data. If these show a significant degree of autocorrelation, then this can be further quantified as a function of distance by calculating a variogram and using it in a regression study.

This regression may be most effectively performed on the analysis of crop yields according to the reciprocal per-plant yield equation:

$$\frac{N_{1,t}}{Y_{1,t}} = \mu + \eta_t + \beta_j + \sum_{q=2}^{n} \rho_q N_{q,t} + \varepsilon_{ij,t}$$

where it is now understood that the residuals display some spatial autocorrelation according to the aforementioned variogram, and the regression moves from an ordinary least squares (OLS) methodology to a general least squares (GLS) methodology (Reich and Davis, 2000).

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6.7 References

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Source	Variable	df	E{MS}
Block	β_j	$4-1=3$	$\sigma^2 + pv\sigma^2_{\alpha\beta} + psv\sigma^2_{\beta}$
Rot	α_r	$2-1=1$	$\sigma^2 + pv\sigma^2_{\alpha\beta} + pnv\theta^2_{\alpha}$
Rot*Block	$(\alpha\beta)_{rj}$	$(4-1)(2-1)=3$	$\sigma^2 + pv\sigma^2_{\alpha\beta}$
TrtProg	γ_k	$4-1=3$	$\sigma^2 + v\sigma^2_{\alpha\beta\gamma} + nsv\theta^2_{\gamma}$
Rot*TrtProg	$(\alpha\gamma)_{rk}$	$(4-1)(2-1)=3$	$\sigma^2 + v\sigma^2_{\alpha\beta\gamma} + nv\theta^2_{\alpha\gamma}$
Block*Rot*TrtProg	$(\alpha\beta\gamma)_{rjk}$	$(4)(4-1)(2-1)=12$	$\sigma^2 + v\sigma^2_{\alpha\beta\gamma}$
Year	η_t	$5-1=4$	$\sigma^2 + \sigma^2_{\alpha\beta\gamma\eta} + nps\theta^2_{\eta}$
Year*Rot	$(\alpha\eta)_{rt}$	$(5-1)(2-1)=4$	$\sigma^2 + \sigma^2_{\alpha\beta\gamma\eta} + np\theta^2_{\alpha\eta}$
Year*TrtProg	$(\gamma\eta)_{kt}$	$(5-1)(4-1)=12$	$\sigma^2 + \sigma^2_{\alpha\beta\gamma\eta} + ns\theta^2_{\gamma\eta}$
Year*Rot*TrtProg	$(\alpha\gamma\eta)_{rkt}$	$(5-1)(2-1)(4-1)=12$	$\sigma^2 + \sigma^2_{\alpha\beta\gamma\eta} + n\theta^2_{\alpha\gamma\eta}$
Block*Year*Rot*Trt	$(\alpha\beta\gamma\eta)_{rjkt}$	$(4)(5-1)(2-1)(4-1)=48$	$\sigma^2 + \sigma^2_{\alpha\beta\gamma\eta}$
Error	ε_{rjktl}	$(2)(4)(3-1)(4-1)=48$	σ^2

TABLE 6.1, Theoretical ANOVA table for the split-split plot experimental design for a single combination of site and observational timing.

Weed	CC/CR	Fort Collins	Torrington	Scottsbluff
AMARE	CC		X	
CHEAL	CC		X	
KCHSC	CC	X	X	
POLCO	CR	X	X	
Grasses	CC	X	X	

TABLE 6.2, Summary of crop rotation effects, indicating for each species which rotation provided superior control along with an indication of how prolific this finding was among the sites.

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Weed	Best Ctrl	Worst Ctrl	Fort Collins	Torrington	Scottsbluff
AMARE	G/C, Conv	G(1/2), G(Full)		X	X
CHEAL	Conv	G(1/2)	X	X	X
KCHSC		Conv	X	X	X
POLCO		G(1/2)		X	
Grasses		Conv	X	X	X

TABLE 6.3, Summary of herbicide treatment effects, indicating for each species which treatment program provided the best and worst control, along with an indication of how prolific this finding was among the sites.

Gross Profits (Less Seeding Costs)

	G(1/2)	G(Full)	G/C	Conv
CC	$246.42	$253.90	$248.02	$210.36
CR	$404.62	$388.78	$387.05	$325.91

TABLE 6.4, Per-acre gross profits calculated for each combination of crop rotation and herbicide treatment program.

Treatment Costs per Acre

	G(1/2)	G(Full)	G/C	Conv
CC	$15.43	$24.83	$31.74	$31.86
CR	$15.43	$24.83	$77.79	$106.40

TABLE 6.5, Per-acre herbicide treatment costs calculated for each combination of crop rotation and treatment program.

Net Profit Comparison

	G(1/2	G(Full	G/C	Conv
CC	$230.98	$229.06	$216.28	$178.49
CR	$389.19	$363.94	$309.26	$219.50

TABLE 6.6, Per-acre net profits calculated for each combination of crop rotation and treatment program.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.6775	0.6775	0.6775	0.7313	0.7313	0.7313	0.7313
Adj R2	0.6557	0.6557	0.6557	0.6832	0.6832	0.6832	0.6832
# Params	5	5	5	12	12	12	12
# Sig Params	5	5	5	6	6	5	5
Cp	0.09	0.09	0.09	2.7191	2.7191	2.7191	2.7191
AICC				-1012	-1012	-1012	-1012
Y1998							
Y1999	XS	XS	XS		XS	XS	XS
Y2000	XS	XS	XS	XS		XS	XS
Y2001				XS	XS		X
Y2002				XS	XS	X	
ABUTH							
AMARE				X	X	X	X
CCHIN							
CHEAL							
CIRAR				X	X	X	X
CONAR							
DATST							
ECHCG							
EPHDE				X	X	X	X
HELAN				X	X	X	X
KCHSC							
LACSE							
MALNE							
PANMI							
POLAV				X	X	X	X
POLCO	XS	XS	XS				
POLPY							
POROL							
SASKR	XS	XS	XS	XS	XS	XS	XS
SETXX							
SOLNI							
XANST							
GRS	XS	XS	XS	XS	XS	XS	XS
BLF				XS	XS	XS	XS
VLC				X	X	X	X

TABLE 6.7, Candidate models relating corn yields and early-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.6856	0.6803	0.6856	0.7107	0.7065	0.7023	0.7063
Adj R2	0.6643	0.6587	0.6643	0.6735	0.6735	0.6733	0.6732
# Params	5	5	5	9	8	7	8
# Sig Params	5	5	5	5	7	7	5
Cp	-2.53	-1.436	-2.53	0.249	-0.89	-2.005	-0.845
AICC				-1012	-1013	-1014	-1013
Y1998							
Y1999	XS	XS	XS	XS	XS	XS	XS
Y2000	XS	XS	XS	XS	XS	XS	XS
Y2001							
Y2002							
ABUTH							
AMARE				X			
CCHIN							
CHEAL							
CIRAR	XS	XS	XS	XS	XS	XS	XS
CONAR							
DATST				X	XS	XS	X
ECHCG	XS	XS	XS				
EPHDE							
HELAN							
KCHSC							
LACSE							
MALNE							
PANMI							
POLAV							
POLCO	XS		XS	XS			XS
POLPY				X	XS	XS	X
POROL							
SASKR							
SETXX							
SOLNI				X			X
XANST					X		
GRS				XS	XS	XS	XS
BLF		XS			XS	XS	
VLC							

TABLE 6.8, Candidate models relating corn yields and mid-season weed populations.

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	Model 1	**Model 2**	**Model 3**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.7306	0.7219	0.7306	0.8137	0.8137	0.8096	0.8096
Adj R2	0.7124	0.7031	0.7124	0.7735	0.7735	0.7721	0.7721
# Params	5	5	5	14	14	13	13
# Sig Params	5	5	5	9	9	9	9
Cp	15.037	17.719	15.037	7.4257	7.4257	6.6803	6.6803
AICC				-1037	-1037	-1038	-1038
Y1998							
Y1999	XS	XS	XS	XS	XS	XS	XS
Y2000		XS			X		XS
Y2001		XS		X		XS	
Y2002	XS		XS	XS	XS	XS	XS
ABUTH							
AMARE				X	X		
CCHIN							
CHEAL							
CIRAR				X	X	X	X
CONAR							
DATST							
ECHCG							
EPHDE							
HELAN	XS	XS	XS	XS	XS	XS	XS
KCHSC							
LACSE				X	X	X	X
MALNE				XS	XS	X	X
PANMI				XS	XS	XS	XS
POLAV							
POLCO				XS	XS	XS	XS
POLPY							
POROL				XS	XS	XS	XS
SASKR							
SETXX							
SOLNI	XS		XS	XS	XS	XS	XS
XANST	XS	XS	XS	XS	XS	XS	XS
GRS							
BLF							
VLC				X	X	X	X

TABLE 6.9, Candidate models relating corn yields and late-season weed populations.

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Corn and All Weed Populations

	Obs 1	Obs 2	Obs 3
Methodology of Origin	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #1
R2	0.7313	0.7065	0.8137
Adj R2	0.6832	0.6735	0.7735
# Params	12	8	14
# Sig Params	6	7	9
Cp	2.7191	-0.89	7.4257
AICC	-1012	-1013	-1037
Y1998			
Y1999		XS	XS
Y2000	XS	XS	
Y2001	XS		X
Y2002	XS		XS
ABUTH			
AMARE	X		X
CCHIN			
CHEAL			
CIRAR	X	XS	X
CONAR			
DATST		XS	
ECHCG			
EPHDE	X		
HELAN	X		XS
KCHSC			
LACSE			X
MALNE			XS
PANMI			XS
POLAV	X		
POLCO			XS
POLPY		XS	
POROL			XS
SASKR	XS		
SETXX			
SOLNI			XS
XANST		X	XS
GRS	XS	XS	
BLF	XS	XS	
VLC	X		X

TABLE 6.10, Strongest candidate models relating corn yields to early, mid, and late-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.6475	0.6552	0.6475	0.7866	0.7866	0.7755	0.7755
Adj R2	0.6098	0.5725	0.6098	0.6693	0.6693	0.6686	0.6686
# Params	3	6	3	11	11	10	10
# Sig Params	3	6	3	5	5	5	5
Cp	-1.583	3.9291	-1.583	5.5721	5.5721	4.2804	4.2804
AICC				-300.4	-300.4	-300.8	-300.8
Y1998							
Y1999				X		X	
Y2000							
Y2001					X		X
Y2002							
ABUTH				X	X		
AMARE		XS					
CCHIN							
CHEAL		XS				XS	XS
CIRAR				X	X	X	X
CONAR							
DATST	XS	XS	XS	XS	XS	XS	XS
ECHCG				X	X	X	X
EPHDE	XS	XS	XS	XS	XS	XS	XS
HELAN				XS	XS	XS	XS
KCHSC	XS		XS	XS	XS	XS	XS
LACSE							
MALNE							
PANMI							
POLAV							
POLCO		XS					
POLPY							
POROL							
SASKR							
SETXX				X	X	X	X
SOLNI							
XANST							
GRS				X	X	X	X
BLF		XS		XS	XS		
VLC							

TABLE 6.11, Candidate models relating sugarbeet yields and early-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.7459	0.7454	0.7459	0.7629	0.7629	0.7725	0.7725
Adj R2	0.6849	0.6843	0.6849	0.6937	0.6937	0.6934	0.6934
# Params	6	6	6	7	7	8	8
# Sig Params	6	6	6	6	6	5	5
Cp	0.8901	0.9254	0.8901	1.6234	1.6234	2.9101	2.9101
AICC				-305	-305	-304.3	-304.3
Y1998							
Y1999		XS			XS		X
Y2000							
Y2001	XS		XS	XS		X	
Y2002							
ABUTH							
AMARE							
CCHIN							
CHEAL	XS	XS	XS	XS	XS	XS	XS
CIRAR	XS	XS	XS	XS	XS	XS	XS
CONAR							
DATST							
ECHCG							
EPHDE							
HELAN							
KCHSC	XS	XS	XS	XS	XS	XS	XS
LACSE							
MALNE							
PANMI							
POLAV							
POLCO							
POLPY	XS	XS	XS	XS	XS	XS	XS
POROL							
SASKR							
SETXX		XS					
SOLNI							
XANST							
GRS	XS		XS	XS	XS	XS	XS
BLF				X	X	X	X
VLC						X	X

TABLE 6.12, Candidate models relating sugarbeet yields and mid-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.6623	0.6674	0.6623	0.7149	0.7149	0.721	0.6964
Adj R2	0.6123	0.6034	0.6123	0.6318	0.6318	0.6239	0.6236
# Params	4	5	4	7	7	8	6
# Sig Params	4	5	4	4	4	3	4
Cp	-1.402	0.2879	-1.402	1.3879	1.3879	3.019	0.5171
AICC				-299.1	-299.1	-297.8	-299.1
Y1998							
Y1999					X		
Y2000							
Y2001				X		X	
Y2002							
ABUTH							
AMARE	XS	XS	XS	XS	XS	X	XS
CCHIN							
CHEAL	XS	XS	XS	XS	XS	XS	XS
CIRAR							
CONAR							
DATST				X	X	X	X
ECHCG		XS					
EPHDE	XS	XS	XS	XS	XS	XS	XS
HELAN							
KCHSC							
LACSE							
MALNE							
PANMI							
POLAV							
POLCO							
POLPY							
POROL							
SASKR							
SETXX		XS					
SOLNI				X	X	X	X
XANST							
GRS	XS		XS	XS	XS	XS	XS
BLF							
VLC						X	

TABLE 6.13, Candidate models relating sugarbeet yields and late-season weed populations.

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Sugarbeets and All Weed Populations

Methodology of Origin	Obs 1 Adjusted R2 #1	Obs 2 Adjusted R2 #1	Obs 3 Adjusted R2 #1
R2	0.7866	0.7629	0.7149
Adj R2	0.6693	0.6937	0.6318
# Params	11	7	7
# Sig Params	5	6	4
Cp	5.5721	1.6234	1.3879
AICC	-300.4	-305	-299.1
Y1998			
Y1999	X		
Y2000			
Y2001		XS	X
Y2002			
ABUTH	X		
AMARE			XS
CCHIN			
CHEAL		XS	XS
CIRAR	X	XS	
CONAR			
DATST	XS		X
ECHCG	X		
EPHDE	XS		XS
HELAN	XS		
KCHSC	XS	XS	
LACSE			
MALNE			
PANMI			
POLAV			
POLCO			
POLPY		XS	
POROL			
SASKR			
SETXX	X		
SOLNI			X
XANST			
GRS	X	XS	XS
BLF	XS	X	
VLC			

TABLE 6.14, Strongest candidate models relating sugarbeet yields to early, mid, and late-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.639	0.9286	0.639	0.9619	0.9667	0.9638	0.9635
Adj R2	0.6133	0.881	0.6133	0.9183	0.9167	0.9095	0.9089
# Params	1	6	1	8	9	9	9
# Sig Params	1	6	1	6	6	6	6
Cp	33.072	6.9145	33.072	6.7584	8.1589	8.5211	8.5519
AICC				-212.4	-212.5	-211.2	-211.1
Y1998							
Y1999							
Y2000							
Y2001							
Y2002							
ABUTH		XS		XS	XS	XS	XS
AMARE		XS		XS	XS	XS	XS
CCHIN							
CHEAL						X	
CIRAR							
CONAR							
DATST							
ECHCG							
EPHDE					X		
HELAN		XS		XS	XS	XS	XS
KCHSC							X
LACSE							
MALNE							
PANMI							
POLAV							
POLCO				X	X	X	X
POLPY							
POROL							
SASKR							
SETXX							
SOLNI		XS		XS	XS	XS	XS
XANST				X	X	X	X
GRS		XS		XS	XS	XS	XS
BLF	XS		XS				
VLC		XS		XS	XS	XS	XS

TABLE 6.15, Candidate models relating wheat yields and early-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.8491	0.9308	0.8491	0.9345	0.9247	0.9397	0.9308
Adj R2	0.8114	0.8702	0.8114	0.8771	0.8745	0.8708	0.8702
# Params	3	7	3	7	6	8	7
# Sig Params	3	7	3	6	6	4	7
Cp	2.2018	4.6802	2.2018	4.4313	3.0923	6.078	4.6802
AICC				-205.7	-205.5	-205	-204.8
Y1998							
Y1999							
Y2000							
Y2001							
Y2002							
ABUTH		XS					XS
AMARE	XS		XS	XS	XS	XS	
CCHIN							
CHEAL		XS					XS
CIRAR							
CONAR							
DATST							
ECHCG							
EPHDE	XS	XS	XS	X		X	XS
HELAN	XS	XS	XS	XS	XS	XS	XS
KCHSC		XS		XS	XS	X	XS
LACSE							
MALNE							
PANMI							
POLAV							
POLCO				XS	XS	XS	
POLPY							
POROL							
SASKR							
SETXX							
SOLNI							
XANST		XS		XS	XS	XS	XS
GRS							
BLF		XS		XS	XS	X	XS
VLC						X	

TABLE 6.16, Candidate models relating wheat yields and mid-season weed populations.

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	Model 1	Model 2	Model 3	Model 5	Model 6	Model 7	Model 8
Methodology of Origin	Forward Selection	Backward Selection	Stepwise Selection	Adjusted R2 #1	Adjusted R2 #2	Adjusted R2 #3	Adjusted R2 #4
R2	0.7834	0.9402	0.7834	0.9879	0.9879	0.9879	0.9864
Adj R2	0.7501	0.9003	0.7501	0.9637	0.9637	0.9637	0.9593
# Params	2	6	2	10	10	10	10
# Sig Params	2	6	2	8	9	9	9
Cp	43.933	12.892	43.933	9.0129	9.0129	9.0129	9.3747
AICC				-226.7	-226.7	-226.7	-224.9
Y1998							
Y1999							
Y2000							
Y2001							
Y2002							
ABUTH							XS
AMARE		XS		XS	XS	XS	
CCHIN							
CHEAL							X
CIRAR							
CONAR							
DATST		XS		XS	XS	XS	XS
ECHCG	XS		XS		X	X	XS
EPHDE	XS	XS	XS	XS	XS	XS	
HELAN				XS	XS	XS	XS
KCHSC		XS		XS	XS	XS	XS
LACSE							
MALNE							
PANMI							
POLAV							
POLCO		XS		XS	XS	XS	XS
POLPY							
POROL							
SASKR							
SETXX				X	XS		
SOLNI				XS	XS	XS	
XANST		XS		XS	XS	XS	XS
GRS				X		XS	XS
BLF							XS
VLC							

TABLE 6.17, Candidate models relating wheat yields and late-season weed populations.

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Wheat and All Weed Populations

	Obs 1	Obs 2	Obs 3
Methodology of Origin	Adjusted R2 #1	Backward Selection	Adjusted R2 #3
R2	0.9619	0.9308	0.9879
Adj R2	0.9183	0.8702	0.9637
# Params	8	7	10
# Sig Params	6	7	9
Cp	6.7584	4.6802	9.0129
AICC	-212.4		-226.7
Y1998			
Y1999			
Y2000			
Y2001			
Y2002			
ABUTH	XS	XS	
AMARE	XS		XS
CCHIN			
CHEAL		XS	
CIRAR			
CONAR			
DATST			XS
ECHCG			X
EPHDE		XS	XS
HELAN	XS	XS	XS
KCHSC		XS	XS
LACSE			
MALNE			
PANMI			
POLAV			
POLCO	X		XS
POLPY			
POROL			
SASKR			
SETXX			
SOLNI	XS		XS
XANST	X	XS	XS
GRS	XS		XS
BLF		XS	
VLC	XS		

TABLE 6.18, Strongest candidate models relating wheat yields to early, mid, and late-season weed populations.

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401 G(1/2)	402 Conv	403 G(Full)	404 G/C	405 Conv	406 G(1/2)	407 G(Full)	408 G/C
301 G/C	302 G(Full)	303 G(1/2)	304 Conv	305 G(Full)	306 G(1/2)	307 G/C	308 Conv
201 G/C	202 G(Full)	203 G(1/2)	204 Conv	205 G(Full)	206 G/C	207 G(1/2)	208 Conv
101 G(1/2)	102 Conv	103 G/C	104 G(Full)	105 G/C	106 G(1/2)	107 Conv	108 G(Full)

CC

CR

FIGURE 6.1, The physical layout of the crop rotations and herbicide treatment programs at the Fort Collins site.

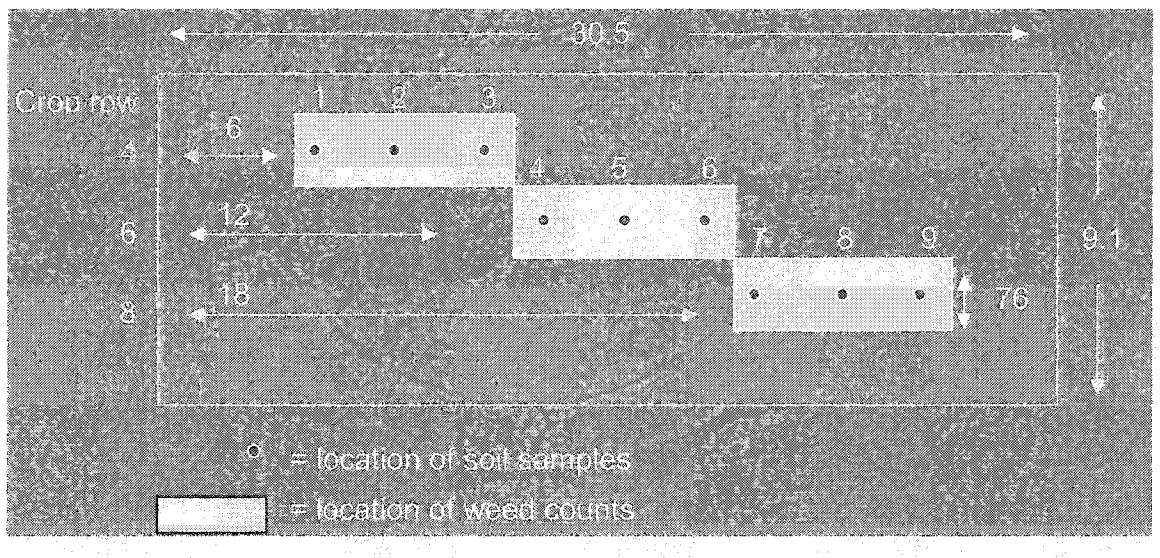

FIGURE 6.2, The physical sampling techniques for soil samples and weed counts.

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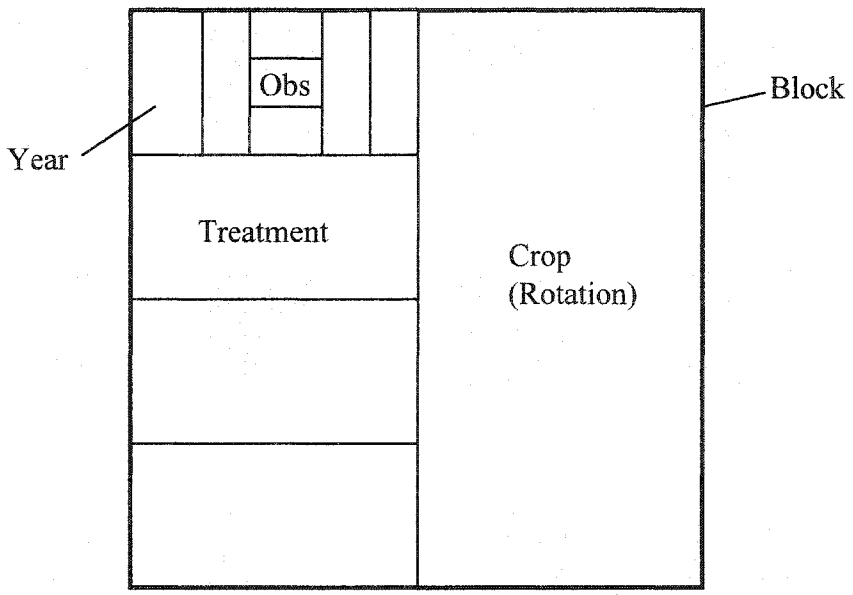

FIGURE 6.3, Spatial/conceptual representation of the data analysis for a single site.

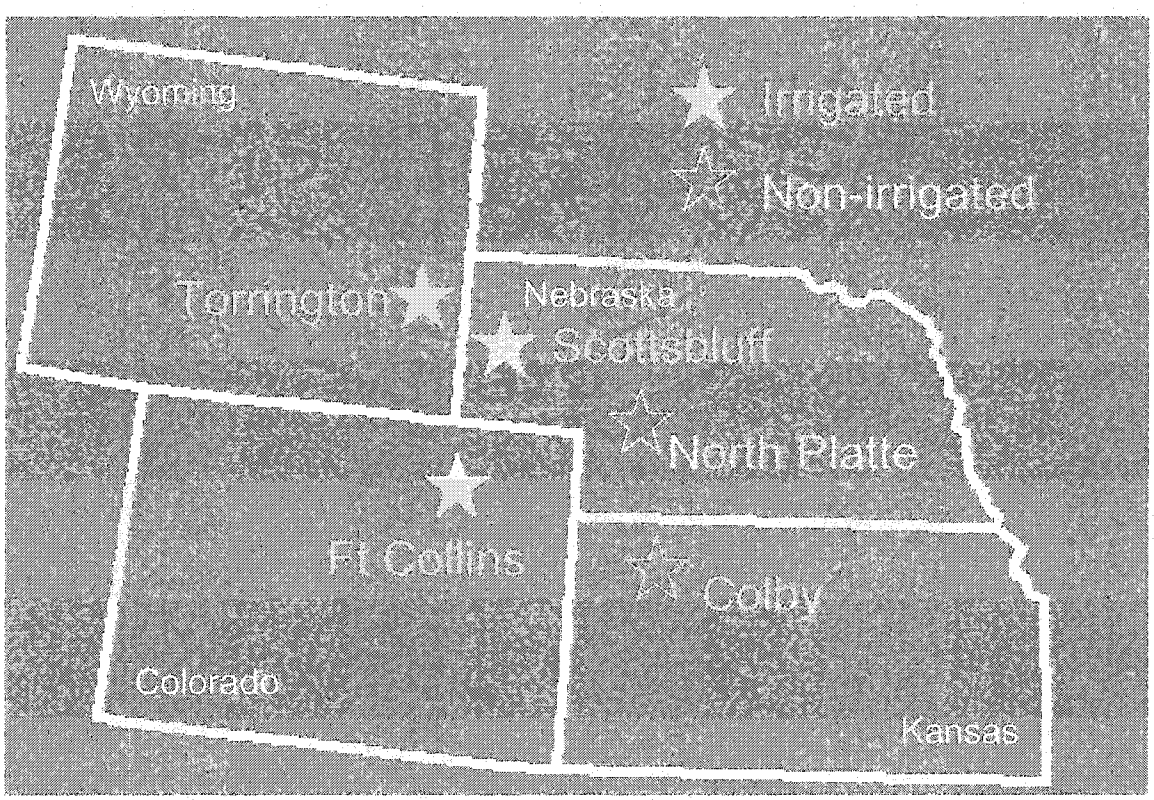

FIGURE 6.4, Site locations involved in the weed shift study.

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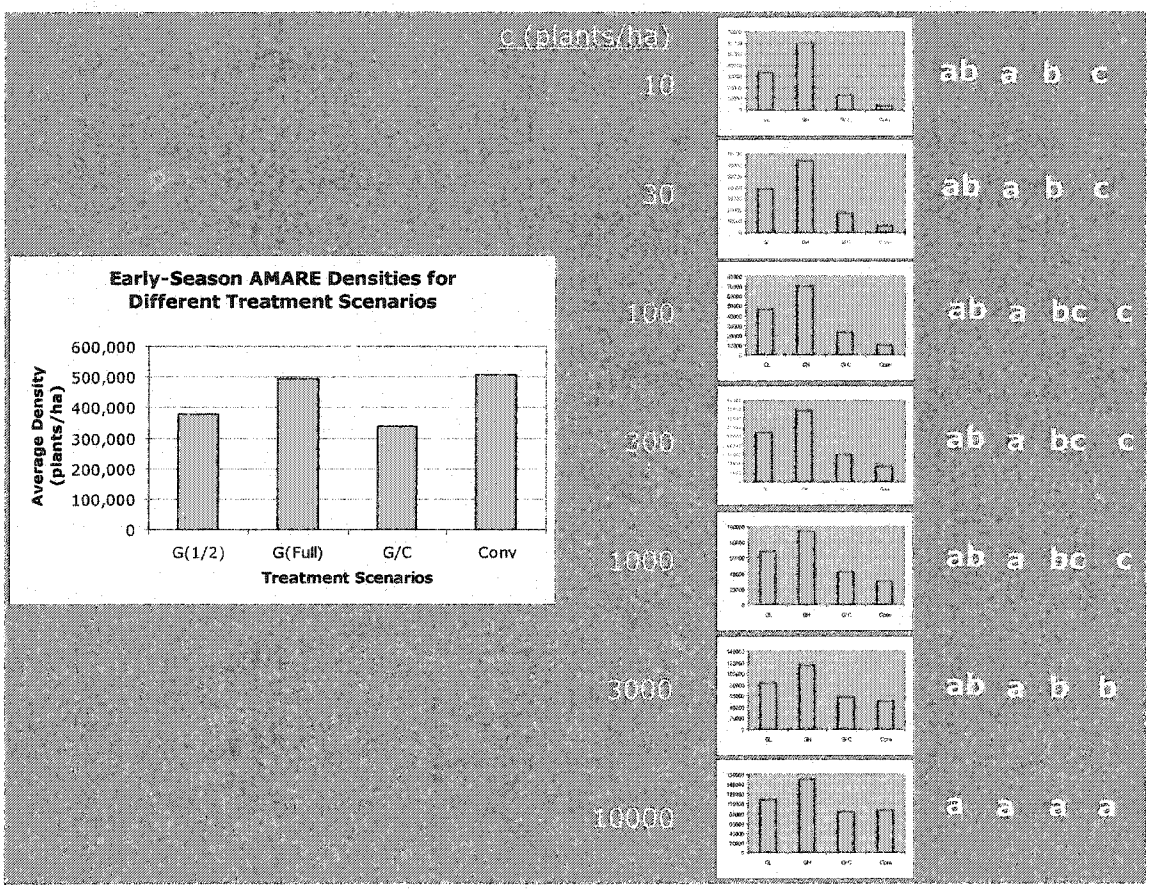

FIGURE 6.5, LSD analyses on early-season redroot pigweed by herbicide treatment at CSU, showing results for different pre-transformation constants, and on the left showing averages of the raw data. Note how the LSD distinctions are dependent upon the choice of constant and most choices contradict the relative arrangement of the raw data averages.

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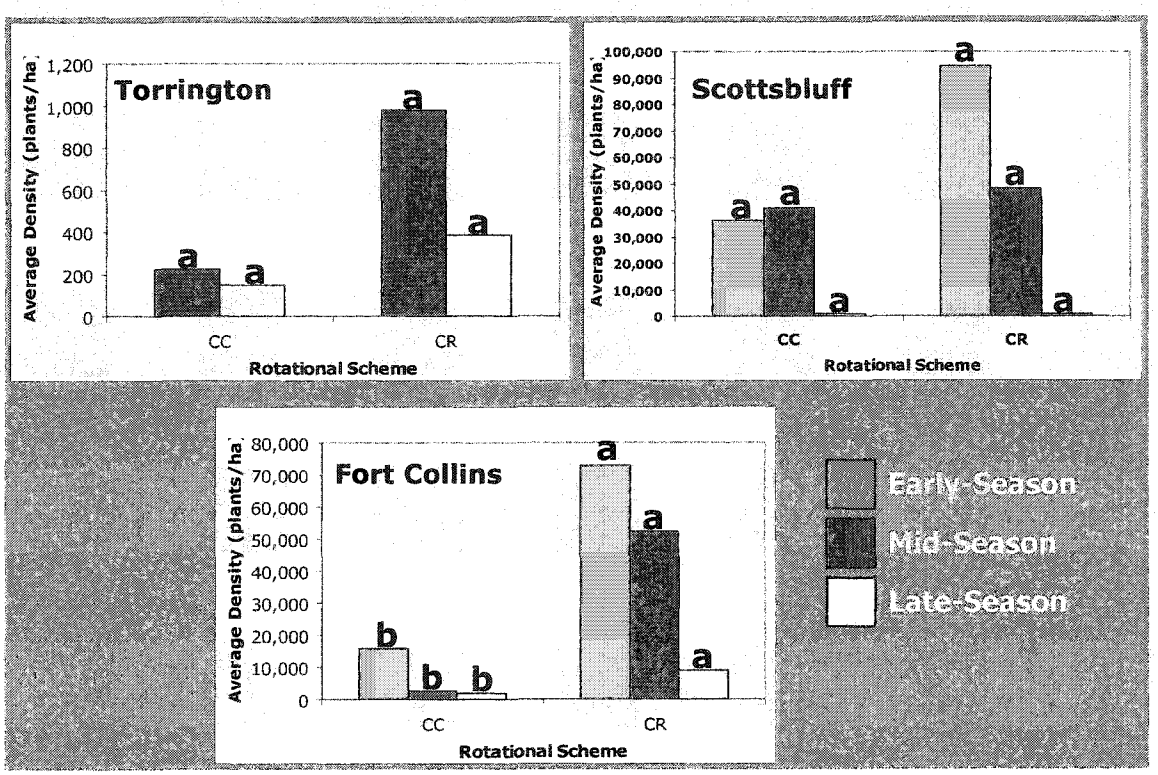

FIGURE 6.6, LSD results with raw data averages for kochia at all three sites displayed by crop rotation.

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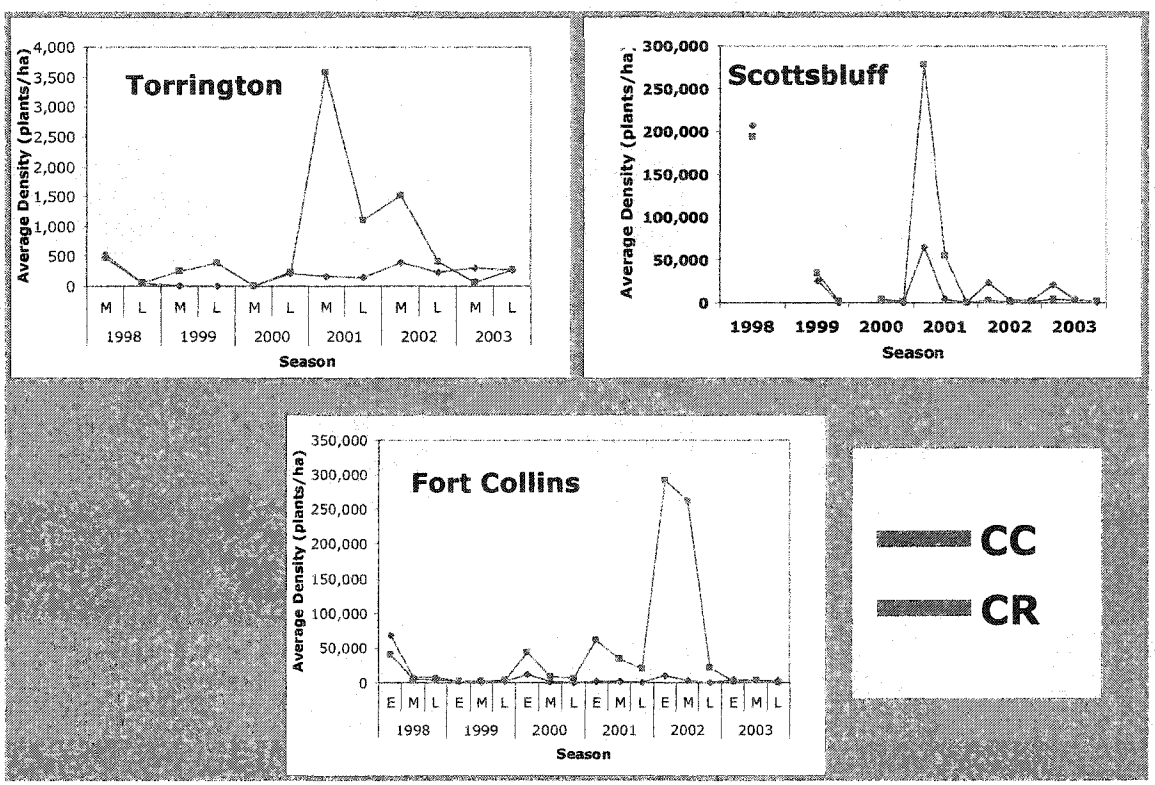

FIGURE 6.7, Trend analyses for kochia at all three sites displayed by crop rotation.

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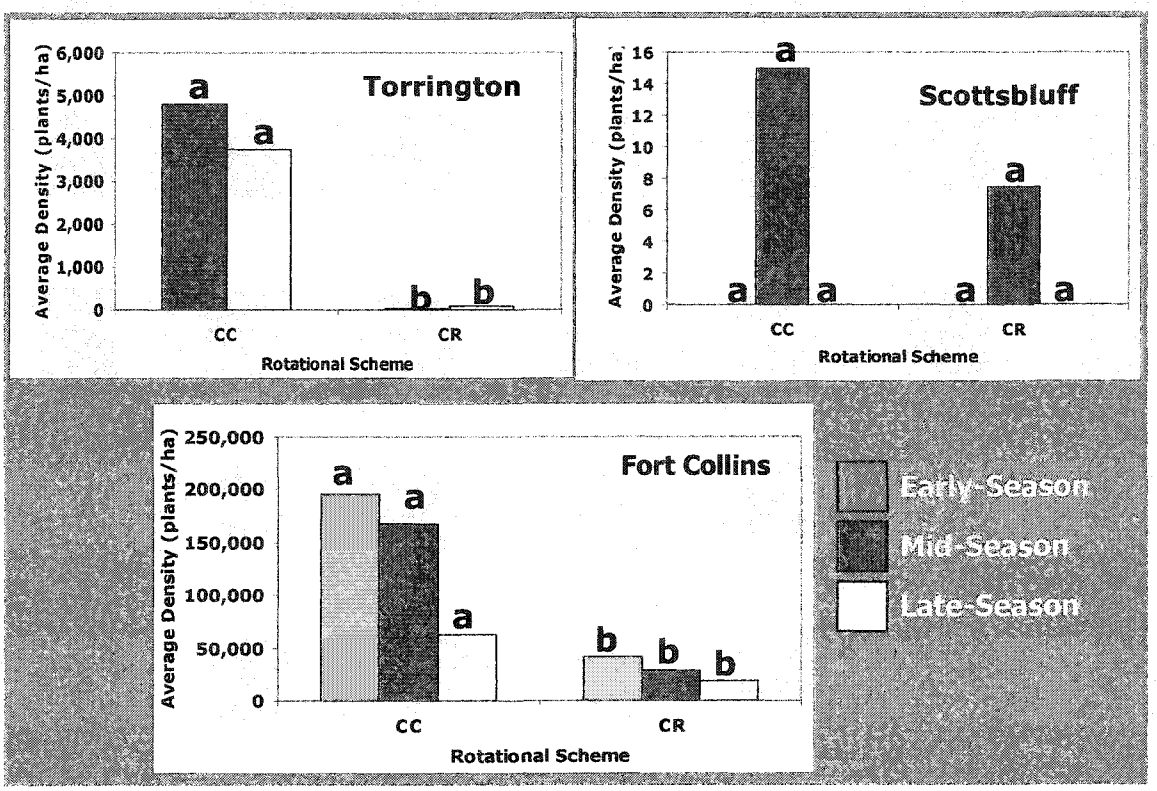

FIGURE 6.8, LSD results with raw data averages for wild buckwheat at all three sites displayed by crop rotation.

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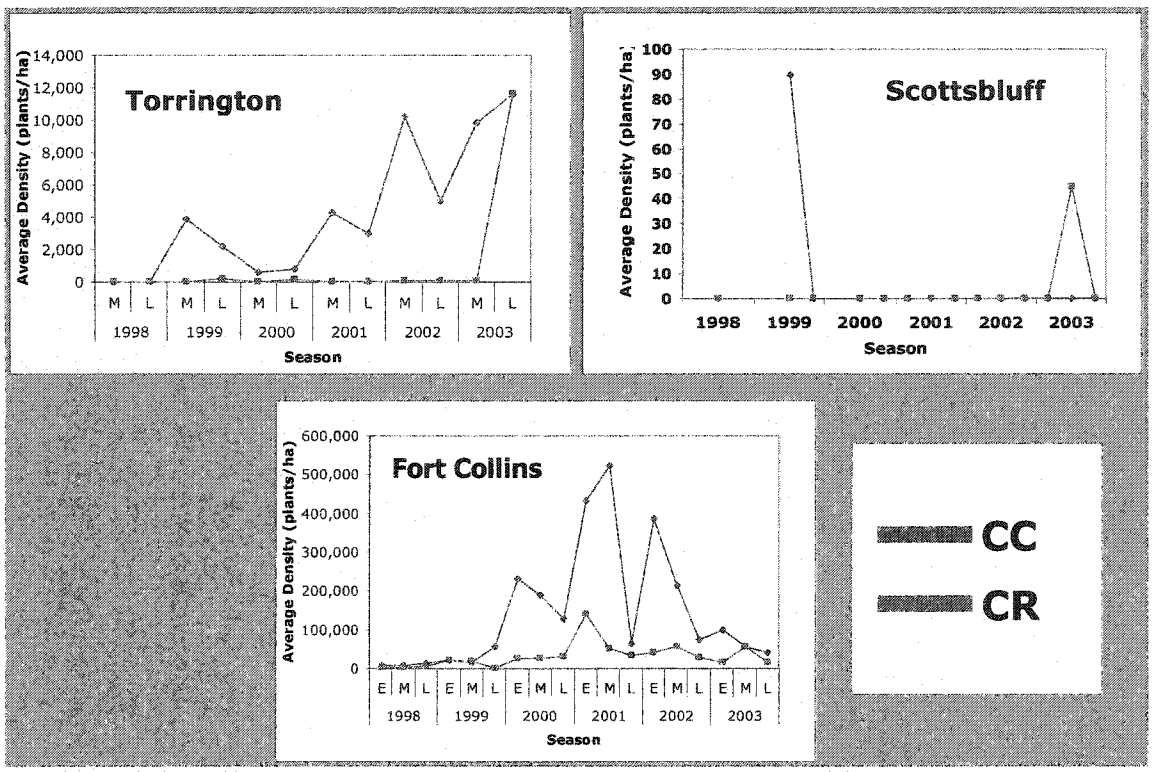

FIGURE 6.9, Trend analyses for wild buckwheat at all three sites displayed by crop rotation.

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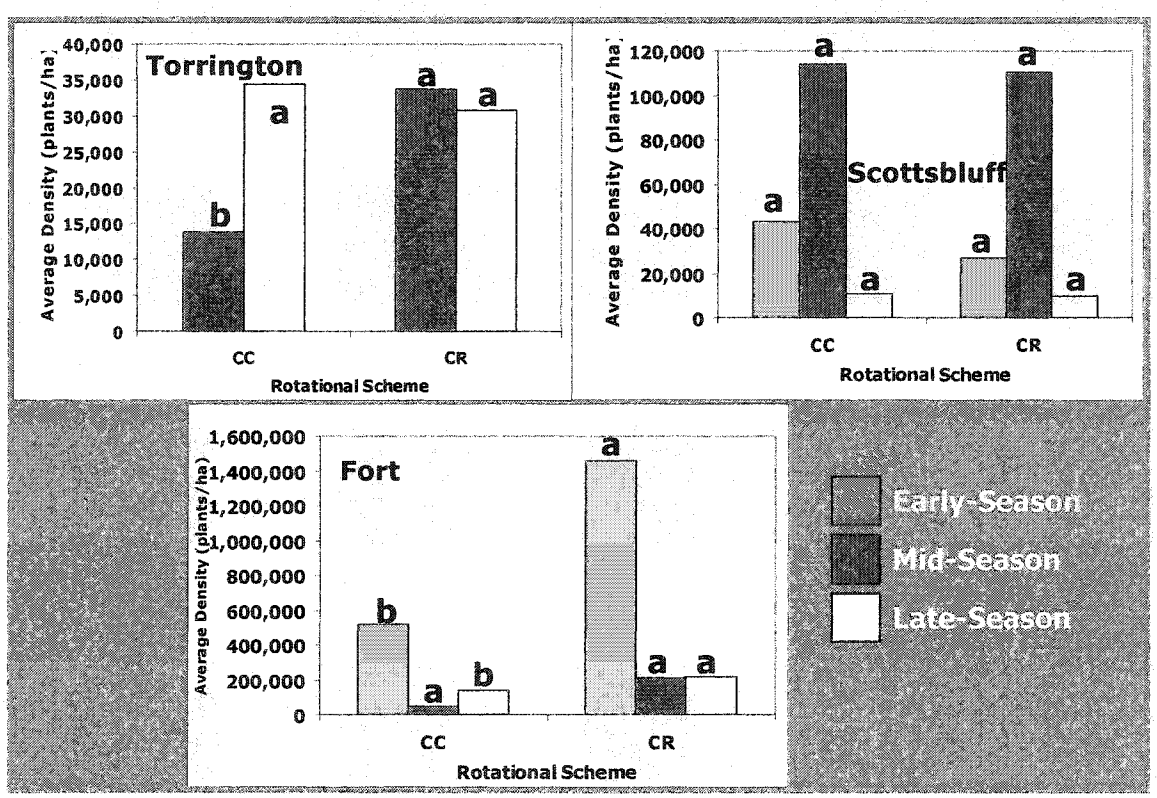

FIGURE 6.10, LSD results with raw data averages for total grasses at all three sites displayed by crop rotation.

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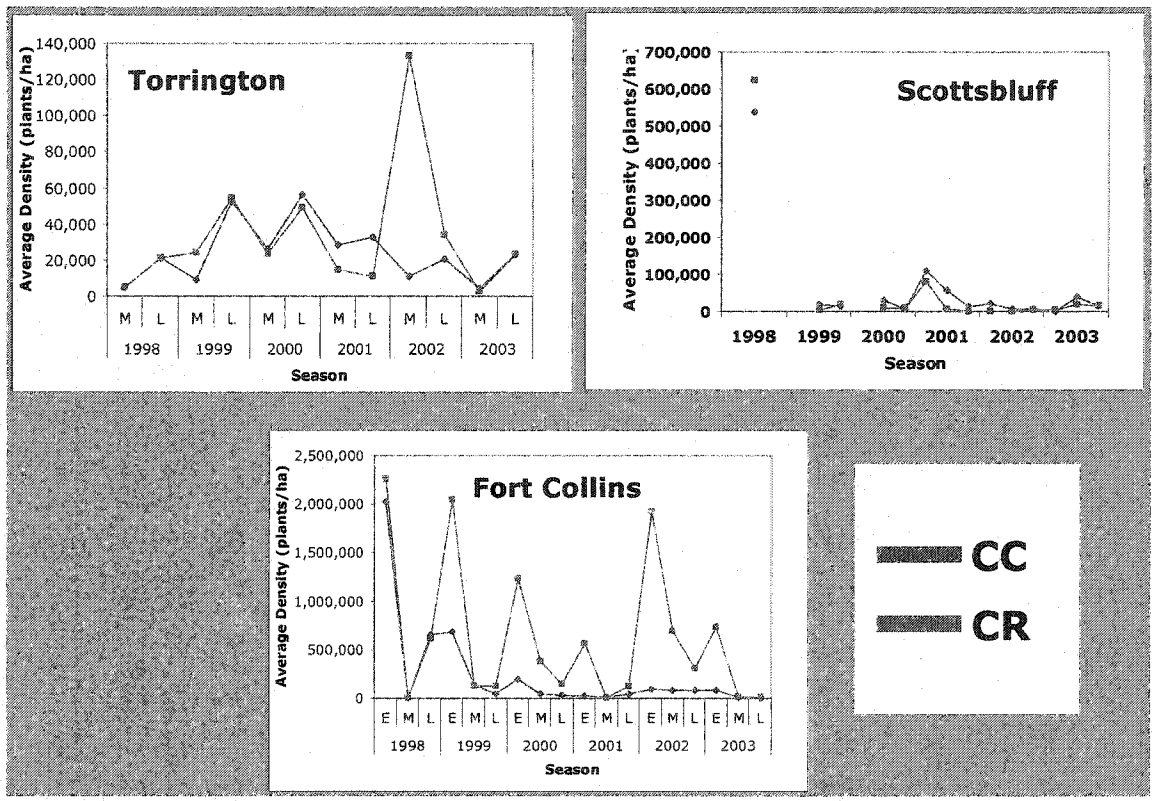

FIGURE 6.11, Trend analyses for total grasses at all three sites displayed by crop rotation.

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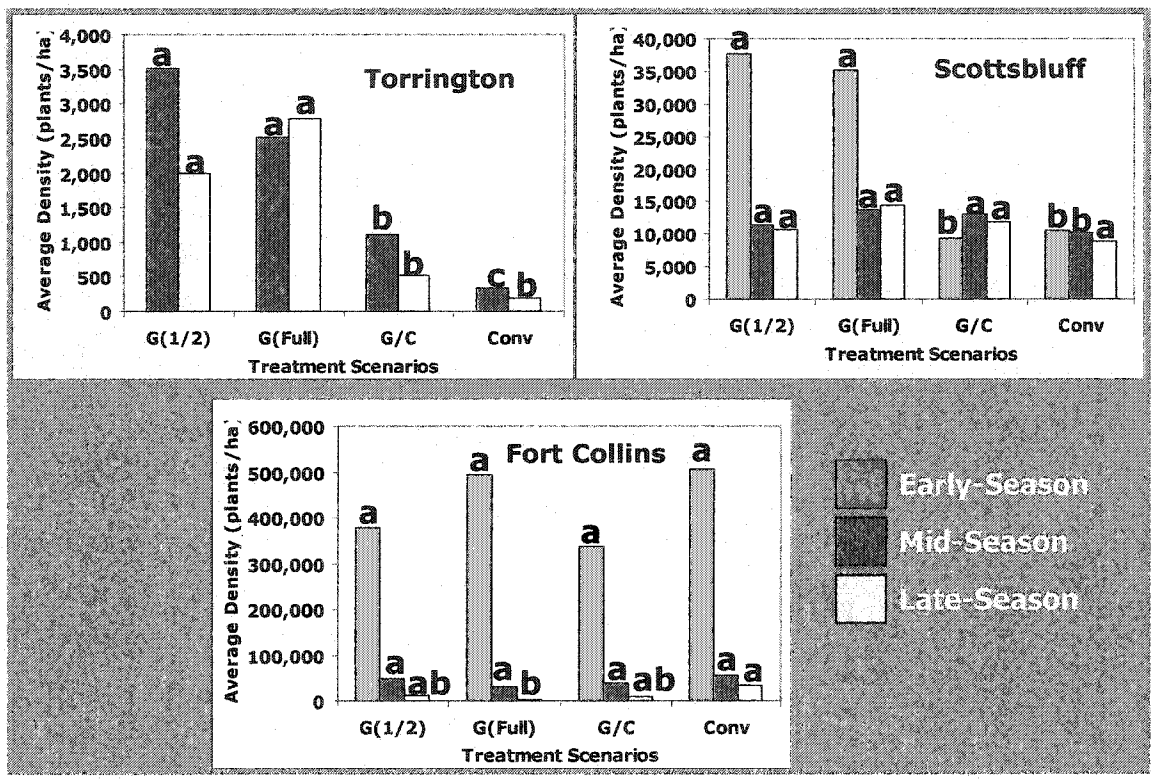

FIGURE 6.12, LSD results with raw data averages for redroot pigweed at all three sites displayed by herbicide treatment program

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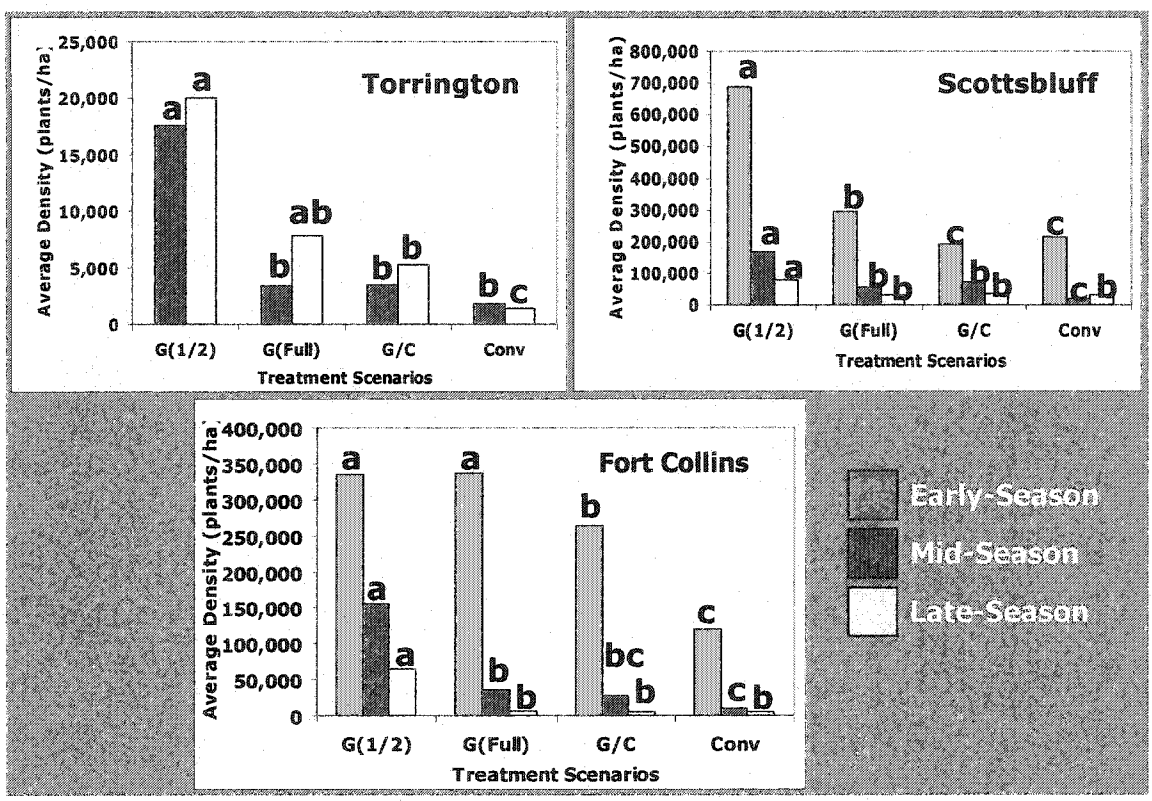

FIGURE 6.13, LSD results with raw data averages for common lambsquarters at all three sites displayed by herbicide treatment program.

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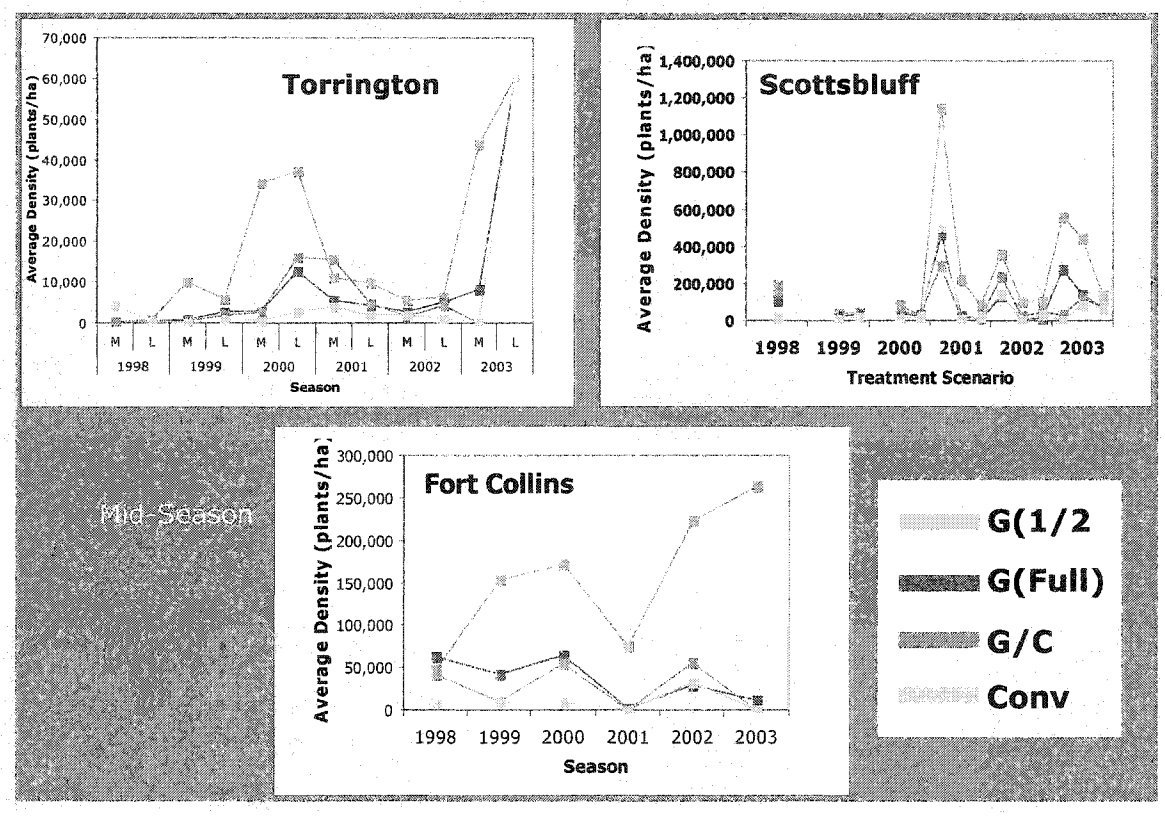

FIGURE 6.14, Trend analyses for common lambsquarters at all three sites displayed by herbicide treatment program. Note that for the Fort Collins site only mid-season populations are displayed.

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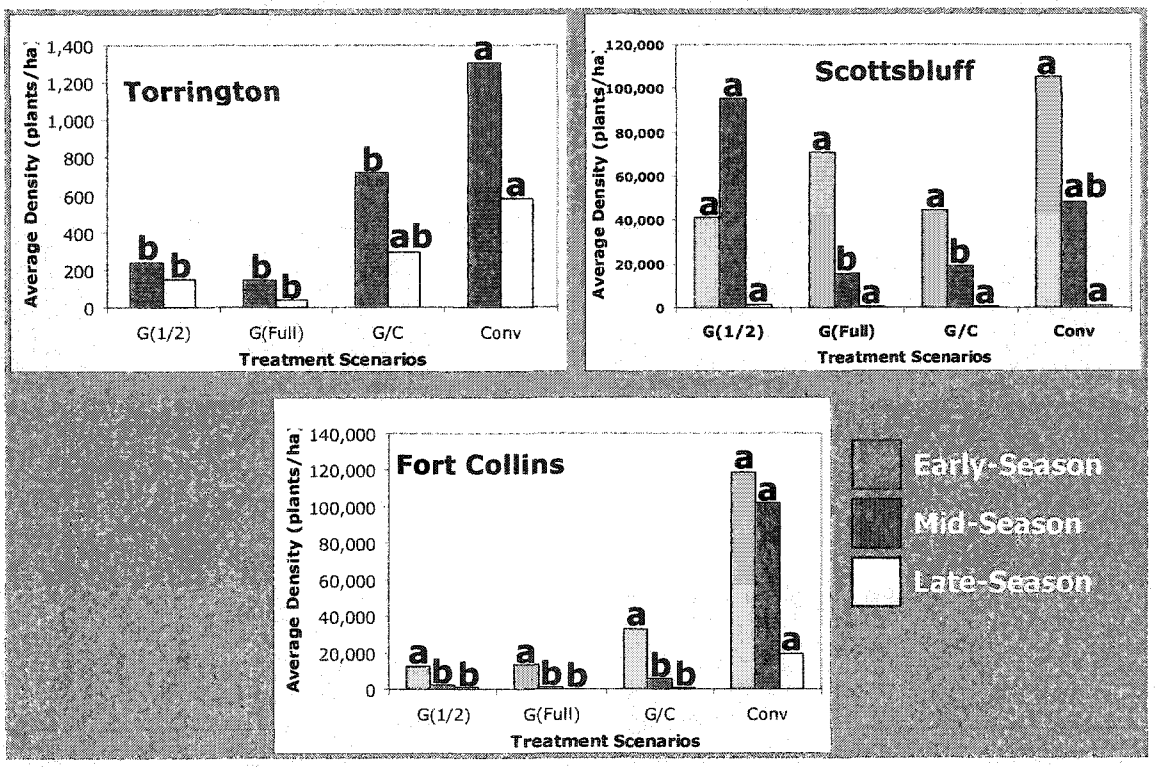

FIGURE 6.15, LSD results with raw data averages for kochia at all three sites displayed by herbicide treatment program.

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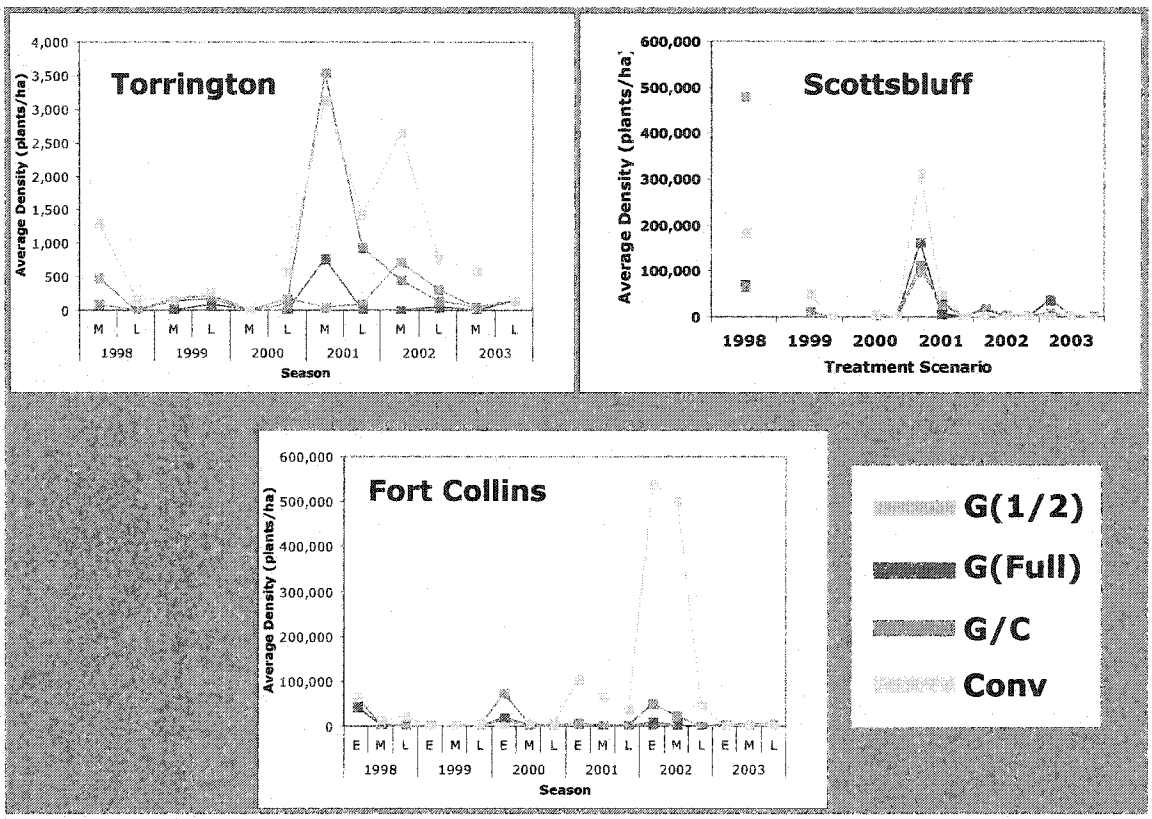

FIGURE 6.16, Trend analyses for kochia at all three sites displayed by herbicide treatment program.

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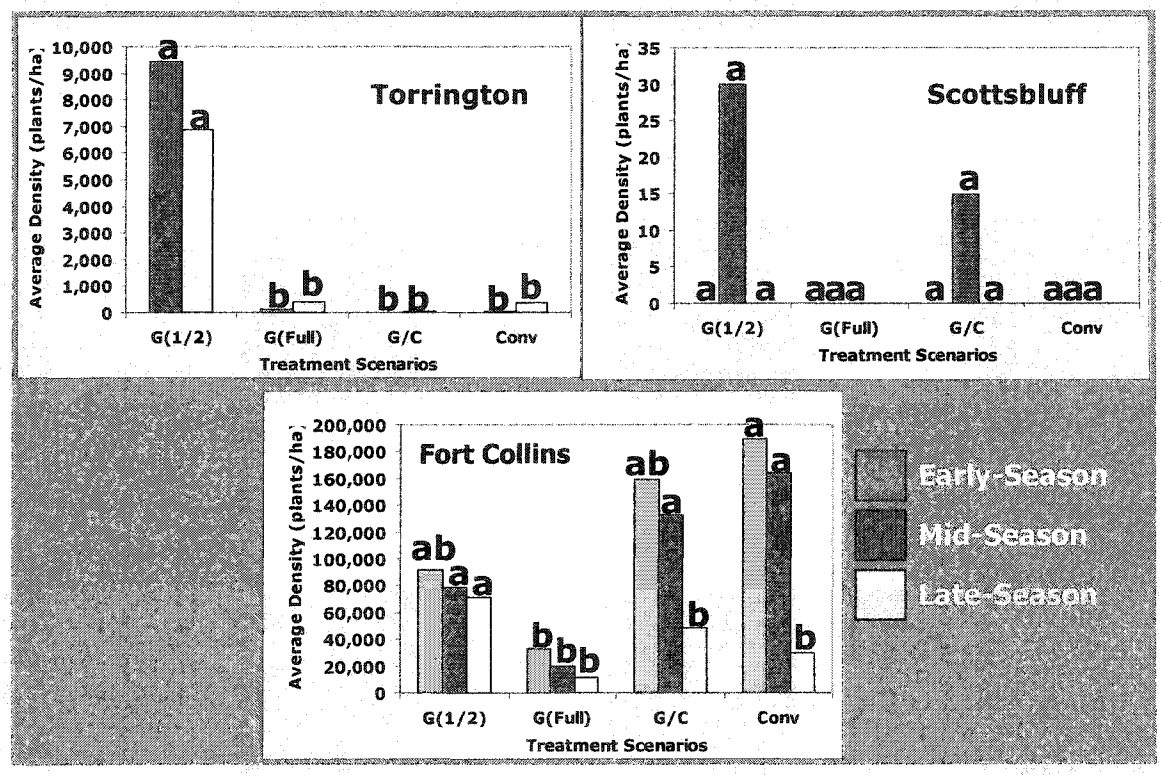

FIGURE 6.17, LSD results with raw data averages for wild buckwheat at all three sites displayed by herbicide treatment program.

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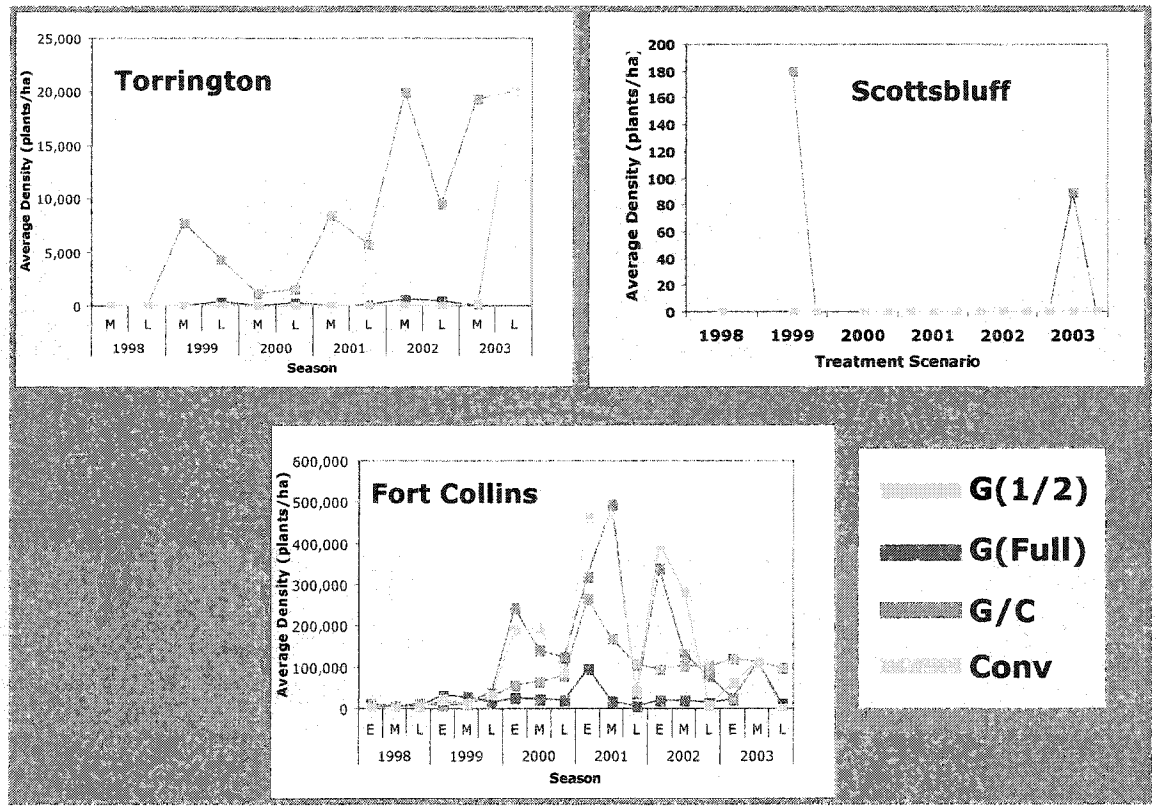

FIGURE 6.18, Trend analyses for wild buckwheat at all three sites displayed by herbicide treatment program.

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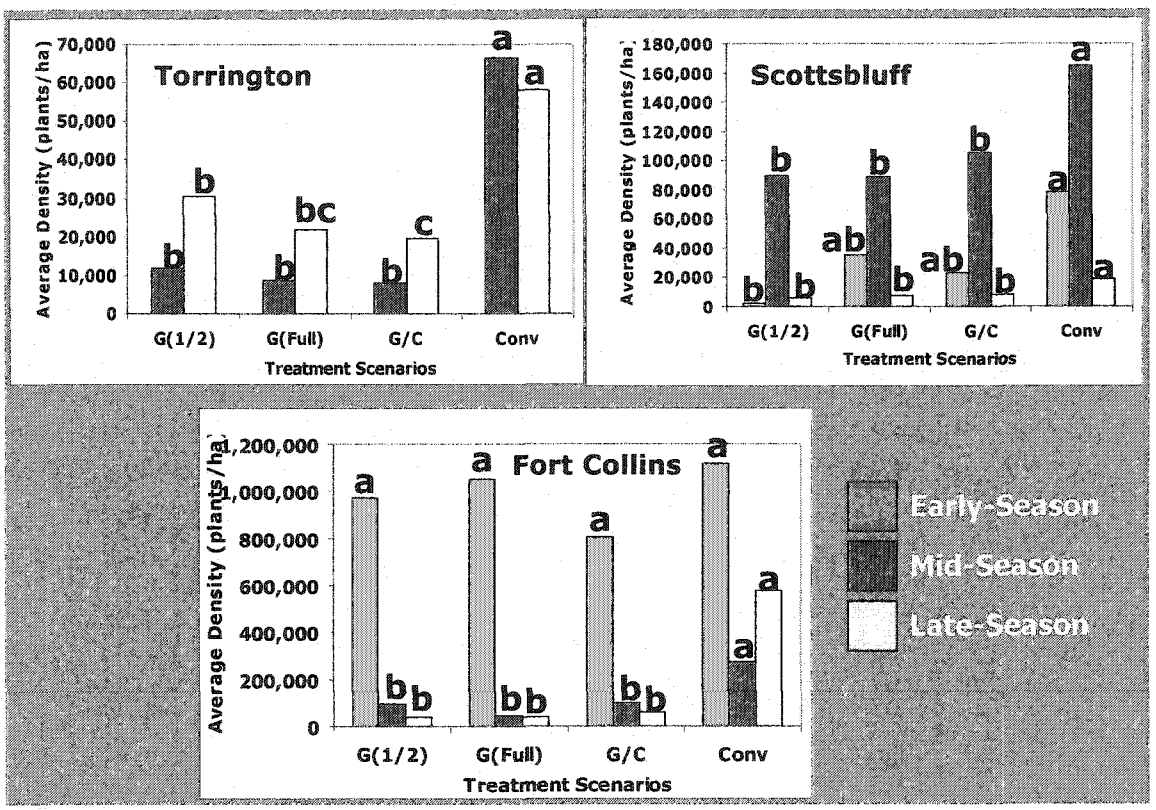

FIGURE 6.19, LSD results with raw data averages for total grasses at all three sites displayed by herbicide treatment program.

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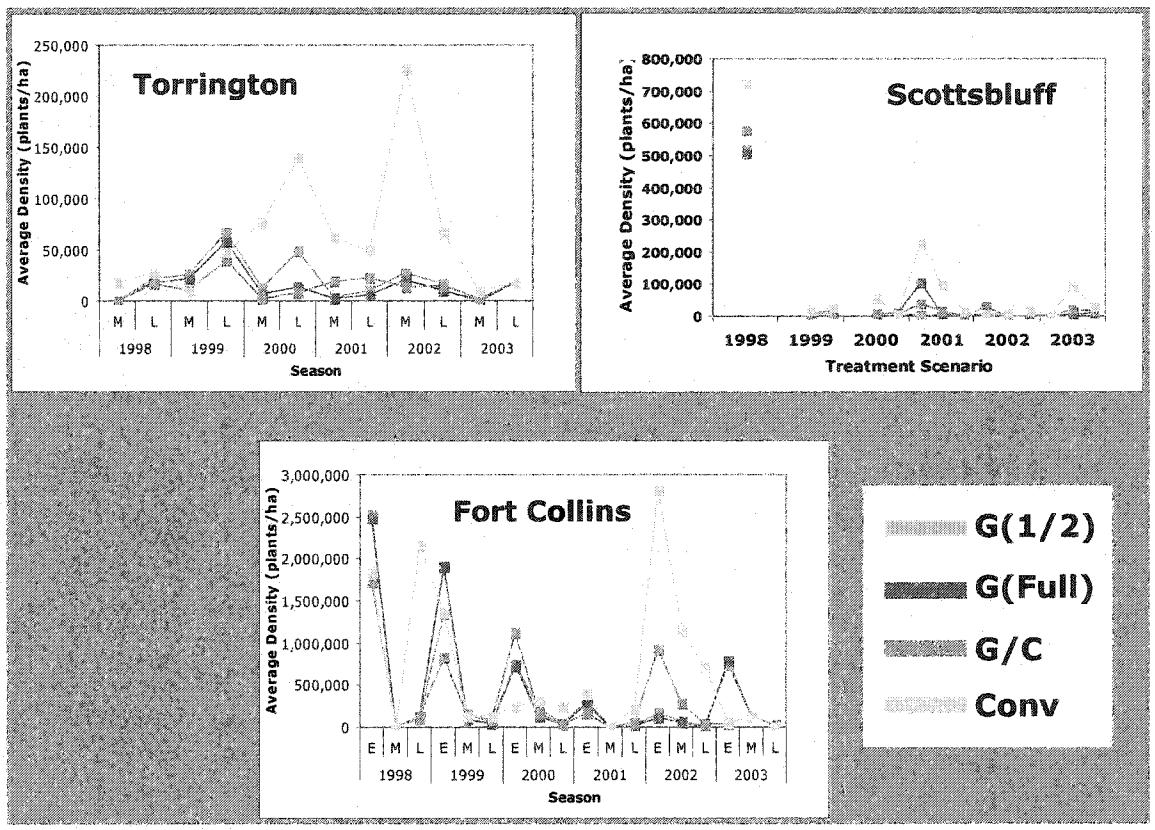

FIGURE 6.20, Trend analyses for total grasses at all three sites displayed by herbicide treatment program.

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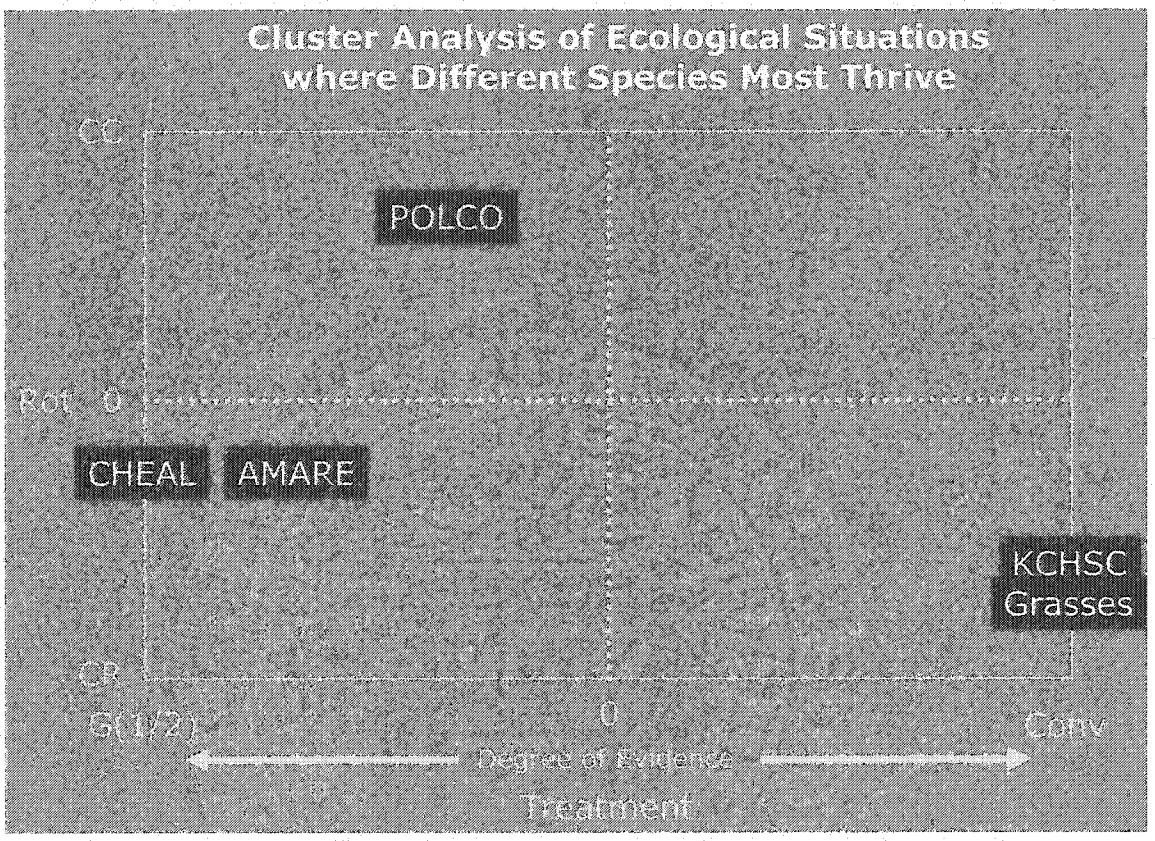

FIGURE 6.21, Cluster analysis summarizing observed ecological differences among analyzed weed species in the study.

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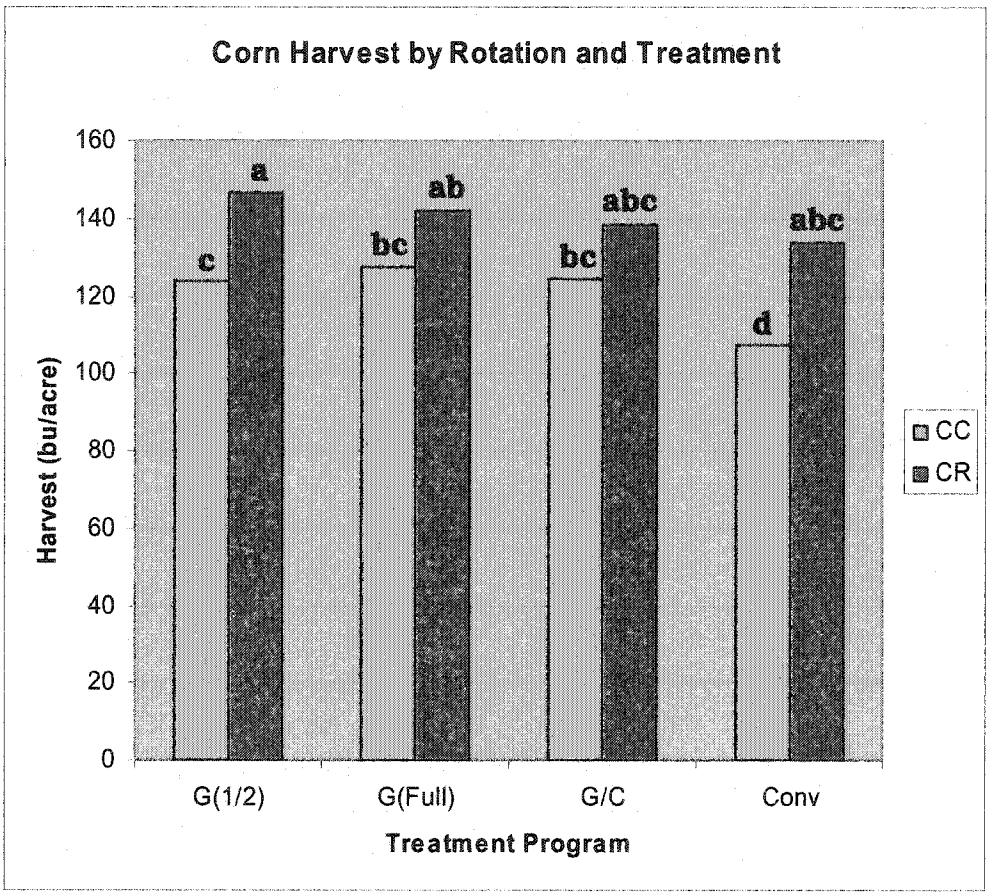

FIGURE 6.22, Average corn harvest values for each combination of crop rotation and herbicide treatment program.

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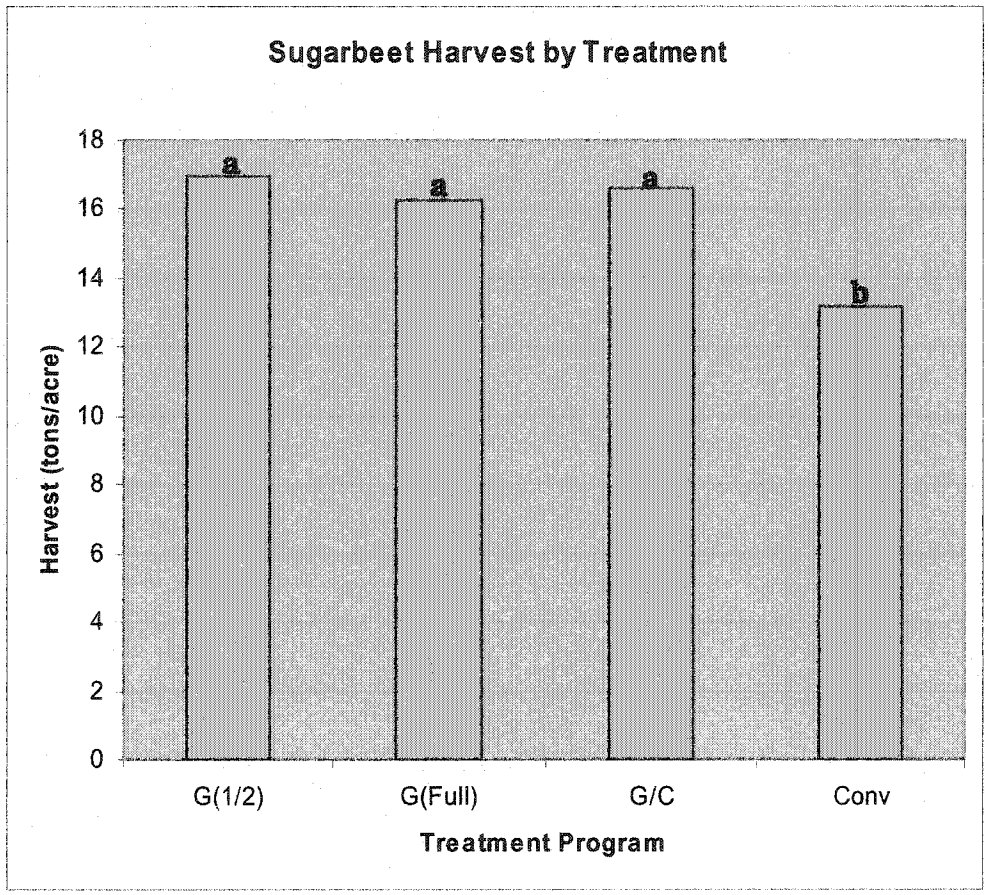

FIGURE 6.23, Same as FIGURE 6.22 but for sugarbeet yields.

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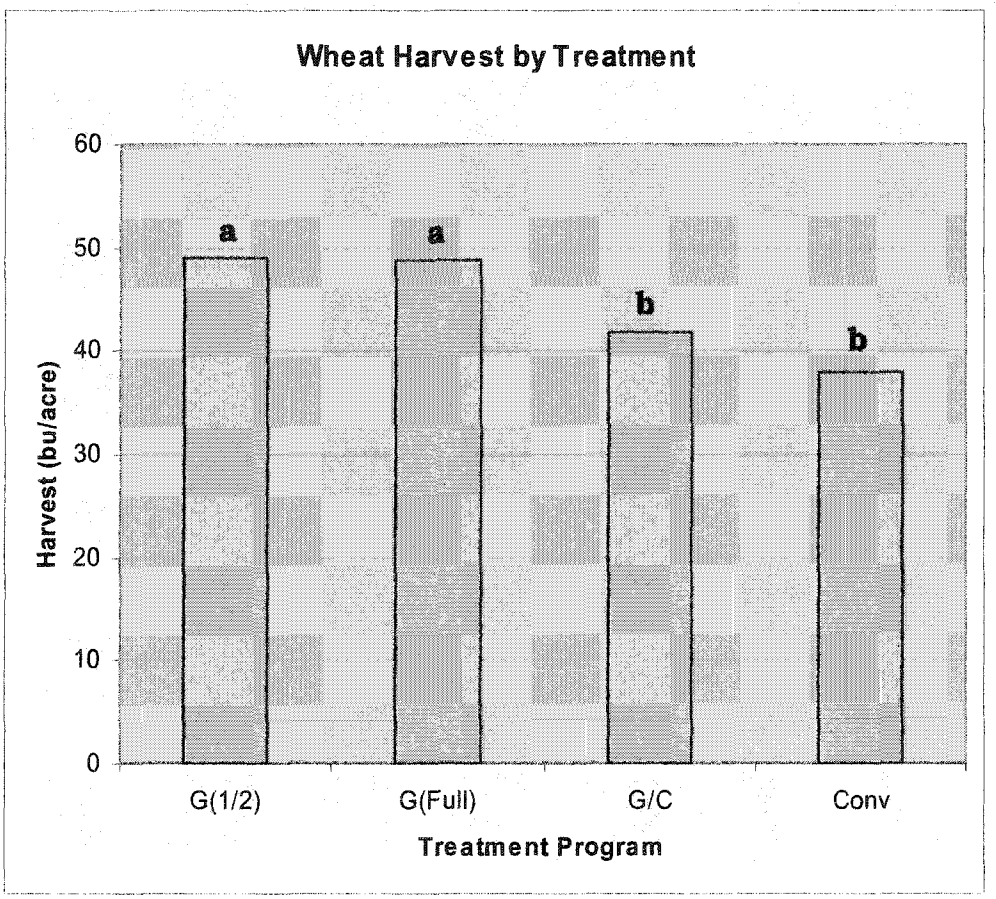

FIGURE 6.24, Same as FIGURE 6.22 but for wheat yields.

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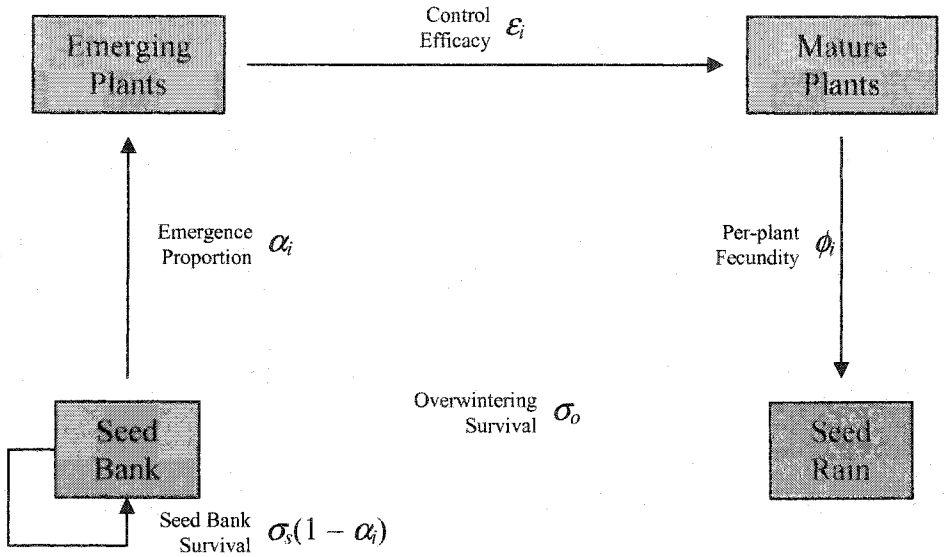

FIGURE 6.25, Model displaying essential demographic processes of weed population dynamics.

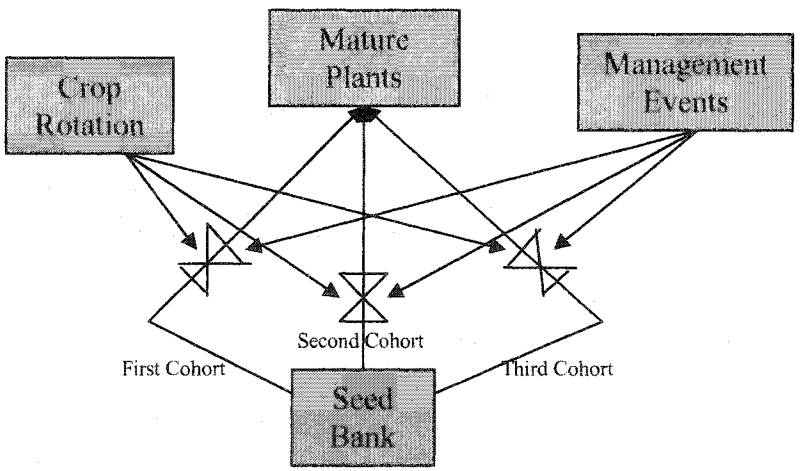

FIGURE 6.26, Model diagram that assesses the direct efficacies that crop rotations and treatment programs (management events) have on the number of seedlings from each cohort that will survive to become mature plants.

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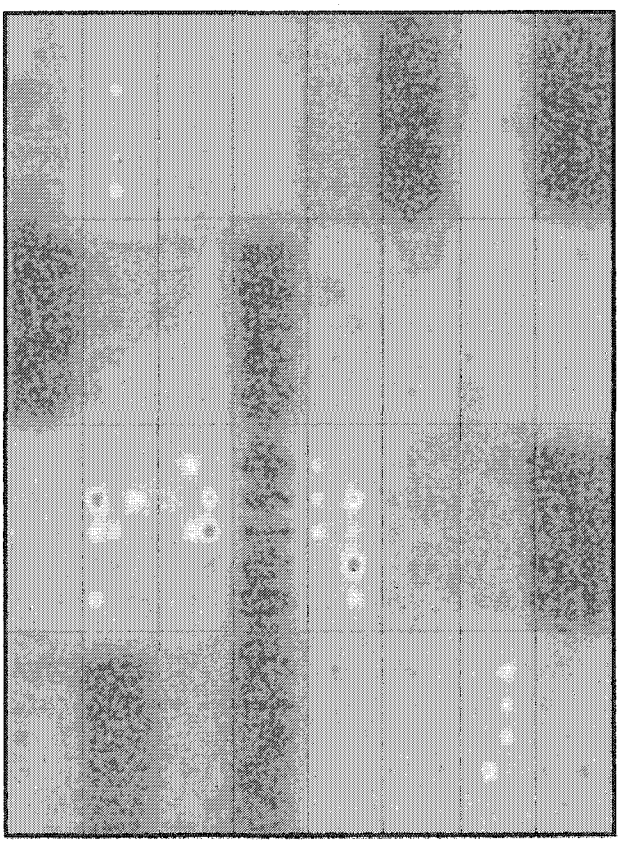

FIGURE 6.27, The spatial arrangement of weed populations in one season at the Fort Collins site.

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Chapter 7.0
The WISDEM Model I: Theory and Enhancements

"Biological modeling involves two key and very different disciplines: biology and mathematics... The best modeling is a happy blend of credible state-of-the-art biology, together with the structure, rigor and clarity of the mathematical approach."
J. France

In section 4.4.3 of chapter 4 the GWM model lineage was introduced (Wiles et al., 1996). Its latest technological heir, known as WISDEM (Weed Interference and Simple Demographic Model) is presented in this chapter in theoretical detail along with a description of its latest algorithmic advancements, some sensitivity analyses, and upgrades to the underlying software and interface.

7.1 Initial Theory Behind the Model

An initial view of the model development is shown in FIGURE 7.1, where the "seed bank" S_t at time t (the quotation marks will be explained in a moment) results in a certain number of emerged plants which are controlled by an efficacy ε so that only the proportion $(1 - \varepsilon)$ of them reach maturity. Each plant at maturity is assigned a fecundity ϕ which results in seed rain. In the "seed bank" the proportion of seed that survives for the year but does not germinate is equal to $\sigma_o\sigma_s(1 - \alpha)$, where the parameters α, σ_s, and

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σ_o respectively correspond to the proportion of seed that germinates and the seed survival rates for the growing season and off season. Thus, an equation that corresponds to FIGURE 7.1 would be the following:

$$S_{t+1} = \sigma_o \sigma_s (1-\alpha) S_t + \sigma_o \phi (1-\varepsilon) \alpha S_t$$

where the first and second terms respectively correspond to dynamics of the seed bank and seed rain. With measurements of seed bank populations being far more costly and time consuming compared to measurements of crop and weed density, the possibility of working exclusively with plant populations and with the seed bank only in an indirect fashion is advantageous. Multiplying both sides of the above equation by the emergence proportion α allows for this to take place:

$$\alpha S_{t+1} = \alpha \sigma_o \sigma_s (1-\alpha) S_t + \alpha^2 \sigma_o \phi (1-\varepsilon) S_t$$

where the term on the left is no longer a value of seed bank population, but a value of total emerged plants for year t (under no control). Herein the assumption is made that potential plant populations for a given year are constantly proportional to seed bank populations. Such an assumption allows for a new variable to be defined, $N_{t,potential}$ which is the potential emerged plants (that is, total emerged plants with no control measures) for year t:

$$N_{t,potential} = \alpha S_t$$

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The equation for potential emerged plants retains much of the appearance of the original seed bank equation:

$$N_{t+1,potential} = \sigma_o \sigma_s (1-\alpha) N_{t,potential} + \sigma_o \phi (1-\varepsilon) \alpha N_{t,potential} \quad [7.1]$$

where the seed bank is indirectly modeled via the dynamics of this "potential density." These two terms can be combined into the following:

$$N_{t+1,potential} = [\sigma_o \sigma_s (1-\alpha) + \sigma_o \phi (1-\varepsilon) \alpha] N_{t,potential}$$

where the term in brackets describes an annual growth (or decline) rate of potential density. In the absence of any seed production (100% control or $\varepsilon = 1$) only the first term remains:

$$\sigma_o \sigma_s (1-\alpha)$$

Thus, this defines a minimum growth rate (or maximum decline rate) which indirectly describes ecological effects of seed bank longevity, but is in the form of a more easily observed phenomena of the rate of decline of emerging seedling populations under maximum control. This expression will be described as r_{min}:

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$$r_{\min} = \sigma_o \sigma_s (1 - \alpha)$$

Similarly, the second term in equation [7.1] can also be described in terms of readily observable phenomena. Retaining the use of potential density, the actual final mature plant density after all herbicide treatments is:

$$(1 - \varepsilon_{TEC}) N_{t,potential}$$

where "TEC" denotes "total efficacy of control", which will be defined in a moment. The remaining variables convert this density into seed production, a process that if handled best actually requires a complex function of density. The expression by Cousens (1985) for yield can be written as follows:

$$Y = Y_{\max}\left(\frac{N_c}{n_{50,c} + N_c}\right)\left(1 - \frac{A\kappa_w N_w}{n_{50,c} + \kappa_w N_w + N_c}\right) = Y = Y_{\max} y_c (N_c, N_w)$$

where y_c is a value between zero and one, representing the product of the two latter proportions in parentheses which govern yield losses due to either small cropping densities or interspecific competition. In this way $Y_{\max}$ is a maximum per area yield gained under very high cropping densities with no weeds. The model theorizes based upon the work of Canner, Wiles, and McMaster (2003) that expressions for seed rain by weeds could be of a similar form:

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$$R = R_{\max} y_w (N_c, N_w)$$

where again y_w is a proportion between zero and one and $R_{\max}$ represents maximum per area weed seed production under high weed densities and no other species present. Here:

$$N_w = (1 - \varepsilon_{TEC}) N_{potential}$$

and the goal now is to deduce an expression for y_w. To do this Canner et. al. (2002) postulated the existence of a theoretical interspecific maximum yield defined, in this case, as follows:

$$\frac{N_c + \kappa_w N_w}{n_{50,c} + N_c + \kappa_w N_w}$$

Such an expression would be related to the maximum total biomass of all species combined. (In this example only two species are involved.) With this in mind, a 'proportional yield', y_c, or fraction of this total maximum interspecific yield would be defined as the ratio of the two above quantities:

$$y_c = \frac{\left(\frac{N_c}{n_{50,c} + N_c}\right)\left(1 - \frac{A\kappa_w N_w}{n_{50,c} + N_c + \kappa_w N_w}\right)}{\frac{N_c + \kappa_w N_w}{n_{50,c} + N_c + \kappa_w N_w}}$$

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If it is further postulated that the sum of all proportional yields for all species is 1:

$$y_c + y_w = 1$$

then this value of proportional yield for the weed species is mathematically obtainable:

$$y_w = \left(\frac{\kappa_w N_w}{n_{50,c} + N_c + \kappa_w N_w} \right) \left(\frac{n_{50,c} + AN_c}{n_{50,c} + N_c} \right)$$

This results in the following equation for the reproductive yield of the weed:

$$R_w = R_{\max} \left(\frac{\kappa_w N_w}{n_{50,c} + N_c + \kappa_w N_w} \right) \left(\frac{n_{50,c} + AN_c}{n_{50,c} + N_c} \right)$$

where $R_{\max}$ denotes maximum weed reproductive yield. This same algorithm can be applied to a multi-species context, where at first all species are ranked from 1 for the most competitive species to n for the least competitive species. The proportional yield of each species is defined as follows:

$$y_i = \left(\frac{\kappa_i N_i}{n_{50,1} + \sum_{k=1}^{n} \kappa_k N_k} \right) \left(\frac{n_{50,1} + \sum_{k=1}^{i-1} A_k \kappa_k N_k}{n_{50,1} + \sum_{k=1}^{i-1} \kappa_k N_k} \right) \left(1 - \frac{\sum_{k=i+1}^{n} A_k \kappa_k N_k}{n_{50,1} + \sum_{k=1}^{n} \kappa_k N_k} \right) \quad [7.2]$$

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where in each case A_k is calculated by integrating the following equation over time:

$$A_i = \int_{t_o}^{t_f} \frac{2\overline{A}_i}{1+e^{\gamma_i(t-t_E)}} dt$$

Survival rates of seeds are readily available from seed longevity studies and weed population decline rates observed when weed seed production is fully halted (100% control). To explain emergence and control efficacy, it is postulated that cropping systems interact with weed populations by controlling the timing and intensity of disturbances. This is of special consideration when the aspect of weed emergence cohorts is considered.

Previous studies have indicated that populations of emerging plant cohorts plotted over time are well represented by Weibull distributions (Brown and Mayer, 1988; Bridges et. al., 1989). FIGURE 7.2 shows such a distribution representing the distribution of new emergence over time of a given weed species. Also shown is the timing of an application of an herbicide which is only applied in post-emergence (that is, having no soil activity). Note that, although the shaded emerged plants undergo control at a high efficacy, the treatment has no effect on plants emerging after the application date. In this way the total efficacy of an herbicide program for a given season is determined not only by the intensity of a given weed control event but also the extent to which the timing of the weed control events allow for a large percentage of the emerging plants to be controlled. Tillage events are also handled in a fashion identical to FIGURE 7.2.

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Pre-emergence herbicide applications are treated in much the same way, where a period of soil activity is defined, and the prescribed herbicidal efficacy is applied to all plants emerging in the time interval bound by the time of application and the period of soil activity.

In this way the total efficacy of control, ε_{TEC}, and, thus, the total number of mature plants in FIGURE 7.1 may require computations involving multiple weed control events having impacts on different portions of the emerged population. In addition, it will be shown in a moment how greater weights are placed on early emerging surviving weeds in calculations of crop yield and weed seed production.

Fecundity of surviving plants falls into two related categories – crop yield and weed seed production. It is of some significance that in the present model both processes are treated in identical fashion – that is, the empirical representations of yield loss and seed production are no longer parameterized independently. The equations for crop yield and weed seed production are essentially the same, embracing the intuitively reasonable notion that increases of seed production in one plant species is oftentimes done at the expense of seed production in another. Such was confirmed by Canner et. al. (2002), and its role will be apparent in the following competition algorithm which determines fecundity of both crop and weed in response to populations of surviving mature plants.

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Thus, the model is able to predict long-term weed shifts resulting from agronomic disturbance and multi-species competition using only the following empirical parameters:

1. For each crop:
   a. $n_{50,c}$
   b. γ (the exponential rate of decrease of weed interference after crop emergence takes place)
   c. Number of days from planting to emergence
   d. Standard crop density
   e. Seeds per gram (since planting densities are in pounds/acre)
   f. Harvest efficacies for weed control
   g. Competitive strength (used as A_{max} in the calculation of A values in equation [7.2]. Also used to do competitive plant rankings.)
   h. Y_{max}
   i. Crop Price
2. For each weed (in both irrigated and dryland scenarios):
   a. Weibull parameters
   b. Date of start of emergence
   c. Date of maturity
   d. $n_{50,w}$
   e. Maximum Biomass
   f. R_{max}
   g. Seed survival rate

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3. For each herbicide treatment:
    a. Efficacies for all weeds
    b. Period of soil activity
4. For each tillage practice:
    a. Efficacies for all weeds

Numerous successful model parameterizations have been documented in Canner et. al. (2003) from a variety of sources.

7.2 Algorithmic Advancements

Although WISDEM in its previous form represented in particular some significant theoretical development, FIGURE 7.3 describes the results of some initial validation work done by Canner et al. (2003). In this figure observed densities are shown on the *x*-axis with corresponding simulated densities on the *y*-axis. In particular the reader should note the low observed densities that are significantly overestimated by the model. This issue is further illustrated in FIGURE 7.4, which shows simulated post-season densities of common lambsquarters (*Chenopodium album*) in 10 years of continuous Roundup Ready™ corn with a single application of Roundup™ each year, where the efficacy of the herbicide is set to 99%. Seven lines are displayed, one for each of seven different initial weed densities. In each of the seven instances unrealistic increases in weed

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densities are observed even for this high herbicidal efficacy. These simulated weed densities were associated with equally unrealistic rises in yield losses to the corn crop.

7.2.1 Weed Fecundity Weighting with Emergence Timing

Again, the WISDEM model algorithm is summarized in FIGURE 7.1, where within a season the emergence of a given weed species is continuously distributed according distributions like the one illustrated in FIGURE 7.2. This can be described as a sequence of numerous emergence cohorts, one for every day from the beginning to the end of the emergence distribution. In instances where all cohorts are controlled to the same extent, the yield response is reduced to the following equation obtainable from Cousens (1985):

$$Y = Y_{wf}\left[1 - \frac{IN_{w,potential}\left(1-\varepsilon_H\right)}{e^{c(t_w - t_c)} + IN_{w,potential}\left(1-\varepsilon_H\right)/A}\right] \qquad [7.3]$$

where the density (under an efficacy of 99%) is equal to the remaining 1% of the potential density and the average emergence time $\bar{t}_w$ is equal to the average value of the emergence distribution:

$$\bar{t}_w = \int_{-\infty}^{\infty} t_w p(t_w) dt_w$$

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where $p(t_w)$ is the frequency distribution of emergence taking place at time t_w. Similarly, the seed production for common lambsquarters is similarly reduced to the following:

$$R_w = R_{w,\max}\left[\frac{\kappa_w N_{w,potential}(1-\varepsilon_H)}{n_{50,1}+N_c+\kappa_w N_{w,potential}(1-\varepsilon_H)}\right]$$

All of the above should provide realistic results since these are obtained from direct parameterization. In actuality, however, each cohort is not equally controlled, and in fact the Weibull shape of the emergence curve affords a skewed shape where the majority of the cohorts emerge relatively early, but some later emerging cohorts are represented by tail on the right side of the distribution. Since no application can control all late emerging cohorts in this representation without being scheduled unrealistically late in the season, concern is raised as to what role these uncontrolled cohorts play in the final result.

Such late-emerging cohorts exist in actual field experiments, and their effect on crop yield is modeled by equation [7.3], where the exponential in the denominator regulates an ever-decreasing effect on yield as the cohort becomes increasingly late in the season. Such late cohorts, however, should also possess less fecundity, and, thus, should have a similar decreased effect on weed seed production. Such reduction of fecundity, however, was found to be absent from the present model algorithm.

This reduction in weed fecundity with timing of emergence is most fundamentally implemented in the WISDEM model in the equation for proportional yield:

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$$y_i = \left(\frac{\kappa_i \hat{N}_i}{n_{50,1} + \sum_{j=1}^{i} \kappa_j N_j} \right) \left(\frac{n_{50,1} + \sum_{k=1}^{i-1} A_k \kappa_k N_k}{n_{50,1} + \sum_{k=1}^{i-1} \kappa_k N_k} \right) \left(1 - \frac{\sum_{k=i+1}^{n} A_k \kappa_k N_k}{n_{50,1} + \sum_{k=1}^{n} \kappa_k N_k} \right)$$

where the reader will note that in the numerator of the first proportion a new density is defined for each weed species:

$$\hat{N}_i \text{ : "Reproductive Density" of Species } i$$

where from here on this is distinguished from "Competitive Density", which is the actual plant density. The single appearance in the above equation is the only instance in which reproductive density is utilized, and this distinction insures that all aspects of plant competition remain unchanged, but for purposes of weed seed production the reproductive density provides an equivalent early-season weed density that would produce the same seed production as all uncontrolled cohorts throughout the season. Its placement in the above equation insures that for low densities it has a proportional effect on seed production:

$$\lim_{N_i \to 0} y_i \propto \hat{N}_i$$

The process of implementation is then reduced to the calculation and maintenance of this additional quantity throughout the seasonal model algorithm. Within a given season, the following variables are already defined in WISDEM:

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P_{ij} : Proportion of species i present at time j within the season

E_{ij} : Proportion of species i emerged at time j within the season

C_{ij} : Proportion of species i successfully controlled at time j within the season

All of the above variables are represented as a proportion of the potential density, where the proportional density is the total density of species i that would occur under no control. Thus:

$$0 \le E_{ij} \le 1 \qquad 0 \le C_{ij} \le 1 \qquad 0 \le P_{ij} \le 1$$

and the actual density at any moment in the season would be found by:

$$N_{ij} = P_{ij} N_{i,potential} \qquad [7.4]$$

where $N_{i,potential}$ is the potential density of species i. (This can also be understood as the weed density under no control.) By definition for each species at any time j:

$$P_j = E_j - C_j \qquad [7.5]$$

where from here on for simplicity the subscript i will be omitted with the understanding that at any given moment only one species is being described. WISDEM updates the variable for proportion controlled via:

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$$C_j = C_{j-1} + (E_j - C_{j-1})\varepsilon_j \qquad [7.6]$$

where a control event acts with an efficacy ε_j:

$$0 \leq \varepsilon_j \leq 1$$

on the difference between total control from the previous time step and the total emergence from the present time step. Thus, each time step involves the following time steps:

1. Updating total emergence (E_j) via the appropriate Weibull distribution
2. Updating total control (C_j) via equation [7.6]
3. Updating total present (P_j) via equation [7.5]

and, again, at the end of the season the final weed density is calculated using equation [7.4]. Combining equations [7.5] and [7.6] this becomes:

$$\begin{aligned} P_j &= E_j - C_j \\ &= E_j - C_{j-1} - (E_j - C_{j-1})\varepsilon_j \\ &= (E_j - C_{j-1})(1 - \varepsilon_j) \\ &= [E_j - (E_{j-1} - P_{j-1})](1 - \varepsilon_j) \end{aligned}$$

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$$= (E_j - E_{j-1})(1 - \varepsilon_j) + P_{j-1}(1 - \varepsilon_j)$$

where the above equation shows two terms that separate the action of the control event between the preexisting present density and the newly emerging cohort.

Incidentally, for soil-applied herbicides WISDEM only applies the herbicide efficacy to the new emergence displayed in the first term, whereas for post-emergence control events the efficacy is applied to both terms as above. Implicitly this omission of the efficacy in the second term for soil-applied herbicide events prevents such events from having an undue multiple set of opportunities to effectuate control on the same cohort and assumes that even if a soil-applied herbicide remains active that any weeds that have successfully survived the herbicide during the previous time period will continue to survive the same soil-applied treatment in the present time period.

Thus, calculations of competitive density throughout the season can be summarized as follows:

Beginning of weed emergence: $P_j = 0$

Events where no control is occurring: $P_j = P_{j-1} + (E_j - E_{j-1})$

Control via a soil-applied herbicide: $P_j = P_{j-1} + (E_j - E_{j-1})(1 - \varepsilon_j)$

Control via a post-emergence event: $P_j = P_{j-1}(1 - \varepsilon_j) + (E_j - E_{j-1})(1 - \varepsilon_j)$

Calculation of final post-season density: $N = P_j N_{potential}$

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With the calculation of reproductive density, weighting must be applied to each cohort according to its time of emergence. Thus, calculations associated with this new variable take the same general form but include this weighting on the term involving new emergence:

Beginning of weed emergence: $\hat{P}_j = 0$

Events where no control is occurring: $\hat{P}_j = \hat{P}_{j-1} + (E_j - E_{j-1})\hat{w}_j$

Control via a soil-applied herbicide: $\hat{P}_j = \hat{P}_{j-1} + (E_j - E_{j-1})(1-\varepsilon_j)\hat{w}_j$

Control via a post-emergence event: $\hat{P}_j = \hat{P}_{j-1}(1-\varepsilon_j) + (E_j - E_{j-1})(1-\varepsilon_j)\hat{w}_j$

Calculation of final post-season density: $\hat{N} = \hat{P}_j N_{potential}$

where $\hat{w}_j$ is the weighting function at time j:

$$0 \le \hat{w}_j \le 1$$

and $\hat{P}_j$ and $\hat{N}$ are respectively analogous to P_j and N but for reproductive density.

The calculation of $\hat{w}_j$ involves the use of the functions defined previously:

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Grasses $$w(t) = \begin{cases} 1 & t \le t_0 \\ 1 - r(t - t_0) & t > t_0 \end{cases}$$ (linear)

Broadleaves $$w(t) = \begin{cases} 1 & t \le t_0 \\ e^{-r(t-t_0)} & t > t_0 \end{cases}$$ (exponential)

In both instances above two parameters are involved, a starting point t_0 in which the weighting function begins to decrease from 1, and a rate of decrease r. In making a discrete interpretation of a continuous weighting function, assumptions must be made. Here the simplifying assumption is made that the weighting function $w(t)$ is equal for all days in the time interval $[t_{j-1}, t_j]$ and is, thus, equally applied to all days. In particular due to the fact that the Weibull function is certainly not constant within the preceding time interval this simplification is not necessarily valid. The alternative to this assumption, however, is to make each of the time steps $[t_{j-1}, t_j]$ a single day in length, which would make the model much more time-consuming to run. Still, the logistics of extending the algorithm to single-day time intervals would not be difficult, and may prove to be a fruitful step if WISDEM is fated to eventually grow into a full-fledged daily-growth competition model. For now, however, the event-based structure remains, with its advantages of speed but disadvantages of time intervals that are large and of unequal size. For this instance the above assumption is necessary, and for its implementation the variable $\hat{w}_j$ is defined as the average value of the function $w(t)$ within the time interval $[t_{j-1}, t_j]$. For the linear function this is as follows:

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$$\hat{w}_j = \frac{1}{t_j - t_{j-1}} \int_{t_{j-1}}^{t_j} 1 - r(t - t_0)dt$$

$$= \frac{1}{t_j - t_{j-1}} \left[t - \frac{r}{2}(t - t_0)^2 \right]_{t_{j-1}}^{t_j}$$

$$= \frac{1}{t_j - t_{j-1}} \left[t - \frac{r}{2}(t - t_0)^2 \right]_{t_{j-1}}^{t_j}$$

$$= \frac{1}{t_j - t_{j-1}} \left[t_j - \frac{r}{2}(t_j - t_0)^2 - t_{j-1} + \frac{r}{2}(t_{j-1} - t_0)^2 \right]$$

$$= \frac{t_j - t_{j-1} - \frac{r}{2}\left[(t_j - t_0)^2 - (t_{j-1} - t_0)^2\right]}{t_j - t_{j-1}}$$

$$= 1 - \frac{r}{2}\left(\frac{t_j^2 - t_{j-1}^2 + 2t_0 t_{j-1} - 2t_0 t_j}{t_j - t_{j-1}} \right)$$

$$= 1 - \frac{r}{2}(t_j + t_{j-1}) - rt_0$$

Thus, for the linear weighting the variable $\hat{w}_j$ is calculated as follows:

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$$\hat{w}_j = \begin{cases} 1 & t_j \le t_0 \\ 1 - \frac{r}{2}\left(t_j + t_{j-1}\right) - rt_0 & t_j > t_0 \end{cases}$$

For the exponential function,

$$\hat{w}_j = \frac{1}{t_j - t_{j-1}} \int_{t_{j-1}}^{t_j} e^{-r(t-t_0)} dt$$

$$= \frac{e^{rt_0}}{t_j - t_{j-1}} \int_{t_{j-1}}^{t_j} e^{-rt} dt$$

$$= \frac{e^{rt_0}}{-r\left(t_j - t_{j-1}\right)} \left[e^{-rt}\right]_{t_{j-1}}^{t_j}$$

$$= \frac{e^{rt_0}}{r}\left(\frac{e^{-rt_{j-1}} - e^{-rt_j}}{t_j - t_{j-1}}\right)$$

Thus, for the exponential weighting the variable $\hat{w}_j$ is calculated as follows:

$$\hat{w}_j = \begin{cases} 1 & t_j \le t_0 \\ \frac{e^{rt_0}}{r}\left(\frac{e^{-rt_{j-1}} - e^{-rt_j}}{t_j - t_{j-1}}\right) & t_j > t_0 \end{cases}$$

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The weighting function for grasses (FIGURE 7.5) is taken from a study by Norris et al. (2001) on barnyardgrass (*Echinochloa crus-galli*) in tomato (*Lycopersicum esculentum*), and the weighting function for broadleaf weeds was taken from two regressions (FIGURES 7.6 and 7.7) on data from Lindquist et al. (1995), where two exponential functions covering reductions in fecundity as well as survival rate were combined into a single exponential weighting function. The latter study was on velvetleaf (*Abutilon theophrasti*) in soybean (*Glycine max*). The weighting function for barnyardgrass is applied equally to all grass species in all cropping situations, and the weighting function for velvetleaf is applied equally to all broadleaf species in all cropping situations. As further such studies on fecundity reduction become available, perhaps the above parameterizations can similarly become more diverse.

For a detailed programmatic description of the implementation of reproductive density into the WISDEM model code the reader is referred to Appendix D.

7.2.2 Crop Competitive Density

WISDEM defines a period of crop competitive vulnerability, but until recently it was not properly implemented. In response to a given date of planting, WISDEM defines two additional dates each season:

t_{CREM} : Crop emergence, or the beginning of the crop competitive period, defined as a specified number of days after the planting date.

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t_{COMP} : End of crop competitive period, defined as a specified number of days after t_{CREM}.

What this appears to do is to define a period of crop competitive vulnerability, defined by the time interval [t_{CREM}, t_{COMP}]. The appropriate implementation of this interval, thus, would involve defining a series of average densities, one for each weed, over this time interval and then using those average densities for the calculation of yield loss. However, prior to this stage of the WISDEM model implementation, such was not occurring. Rather, yield losses were based solely upon the value of the weed densities at t_{COMP}. This is modified in the present version through the definition of "crop competitive density":

$$N_{CCD,i} = \int_{t_{CREM}}^{t_{COMP}} N_i(t) w(t) dt$$

for each species i, where the actual density $N_i(t)$ is averaged over the time interval [t_{CREM},t_{COMP}]. The function $w(t)$ is a weighting function that allows for complex weighting over the above time interval.

Insight into the shape of the function $w(t)$ can be gained from Sattin et al. (1992), who ascribes the following function to the reduction in proportional yield loss with changes in time of weed removal:

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$$y(t_r) = \frac{ae^{kt_r} - a}{1 + ae^{kt_r}}$$

where a and k are parameters and t_r is the time of removal in growing degree days (GDD) since time of crop emergence. Degree of crop competitive vulnerability, thus, describes the degree to which this quantity varies with changes in t_r:

$$w(t) = \frac{dy(t_r)}{dt_r} = \frac{(1 + ae^{kt_r})kae^{kt_r} - (ae^{kt_r} - a)kae^{kt_r}}{(1 + ae^{kt_r})^2} = \frac{ka(1-a)e^{kt_r}}{(1 + ae^{kt_r})^2}$$

Thus,

$$w(t) = \frac{ka(1-a)e^{kt_r}}{(1 + ae^{kt_r})^2}$$

However, since the above integral is calculated on a discrete (and not continuous) basis, calculation of crop competitive density is actually implemented thus:

$$N_{CCD,i} = \sum_{j=1}^{m} N_{ij} \tilde{w}_j$$

where $j \in \{1...m\}$ describes each of the m time steps in the interval $[t_{CREM}, t_{COMP}]$, and $\hat{w}_j$ is a normalized integral of the function $w(t)$ over the j^{th} time interval:

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$$\tilde{w}_j = \frac{\int_{t_{j-1}}^{t_j} w(t)dt}{\int_{t_{CREM}}^{t_{COMP}} w(t)dt}$$

where the denominator of the above proportion makes it so that:

$$\sum_{j=1}^{m} \tilde{w}_j = 1$$

From the fundamental theorem of calculus the calculation of $\hat{w}_j$ becomes:

$$\tilde{w}_j = \frac{y(t_j) - y(t_{j-1})}{y(t_0) - y(t_m)} = \frac{\frac{ae^{kt_j} - a}{ae^{kt_j} + 1} - \frac{ae^{kt_{j-1}} - a}{ae^{kt_{j-1}} + 1}}{\frac{ae^{kt_{COMP}} - a}{ae^{kt_{COMP}} + 1} - \frac{ae^{kt_{CREM}} - a}{ae^{kt_{CREM}} + 1}}$$

Since $t_{CREM} = 0$, then the second fraction in the denominator becomes $\frac{a-a}{a+1} = 0$.

Thus:

$$\tilde{w}_j = \left(\frac{ae^{kt_{COMP}} + 1}{ae^{kt_{COMP}} - a}\right)\left(\frac{ae^{kt_j} - a}{ae^{kt_j} + 1} - \frac{ae^{kt_{j-1}} - a}{ae^{kt_{j-1}} + 1}\right)$$

Thus, the implementation of crop competitive density in WISDEM involves first the definition of the following variable:

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$\tilde{N}_i$: Crop Competitive Density for species i

for each weed species ($i \in \{1...n\}$). Within a given season, the following variables are already defined in WISDEM:

P_{ij} : Proportion of species i present at time j within the season

E_{ij} : Proportion of species i emerged at time j within the season

C_{ij} : Proportion of species i successfully controlled at time j within the season

All of the above variables are represented as a proportion of the potential density, where the proportional density is the total density of species i that would occur under no control. Thus:

$$0 \le E_{ij} \le 1 \qquad 0 \le C_{ij} \le 1 \qquad 0 \le P_{ij} \le 1$$

and the actual density at any moment in the season would be found by:

$$N_{ij} = P_{ij} N_{i,potential} \qquad [7.7]$$

where $N_{i,potential}$ is the potential density of species i. (This can also be understood as the weed density under no control.) By definition for each species at any time j:

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$$P_j = E_j - C_j \quad [7.8]$$

where from here on for simplicity the subscript *i* will be omitted with the understanding that at any given moment only one species is being described. WISDEM updates the variable for proportion controlled via:

$$C_j = C_{j-1} + (E_j - C_{j-1})\varepsilon_j \quad [7.9]$$

where a control event acts with an efficacy ε_j:

$$0 \leq \varepsilon_j \leq 1$$

on the difference between total control from the previous time step and the total emergence from the present time step. Thus, each time step involves the following time steps:

1. Updating total emergence (E_j) via the appropriate Weibull distribution
2. Updating total control (C_j) via equation [7.9]
3. Updating total present (P_j) via equation [7.8]

and, again, at the end of the season the final weed density is calculated using equation [7.7]. Combining equations [7.8] and [7.9] this becomes:

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$$
\begin{aligned}
P_j &= E_j - C_j \\
&= E_j - C_{j-1} - (E_j - C_{j-1})\varepsilon_j \\
&= (E_j - C_{j-1})(1-\varepsilon_j) \\
&= [E_j - (E_{j-1} - P_{j-1})](1-\varepsilon_j) \\
&= (E_j - E_{j-1})(1-\varepsilon_j) + P_{j-1}(1-\varepsilon_j)
\end{aligned}
$$

The final form of the above equation separates the action of the control event between the preexisting present density and the newly emerging cohorts.

Incidentally, for soil-applied herbicides WISDEM only applies the herbicide efficacy to the new emergence displayed in the first term, whereas for post-emergence control events the efficacy is applied to both terms as above. Implicitly this omission of the efficacy in the second term for soil-applied herbicide events prevents such events from having an undue multiple set of opportunities to effectuate control on the same cohort and assumes that even if a soil-applied herbicide remains active that any weeds that have successfully survived the herbicide during the previous time period will continue to survive the same soil-applied treatment in the present time period.

Thus, calculations of competitive density throughout the season can be summarized as follows:

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Beginning of weed emergence: $P_j = 0$

Events where no control is occurring: $P_j = P_{j-1} + (E_j - E_{j-1})$

Control via a soil-applied herbicide: $P_j = P_{j-1} + (E_j - E_{j-1})(1 - \varepsilon_j)$

Control via a post-emergence event: $P_j = P_{j-1}(1 - \varepsilon_j) + (E_j - E_{j-1})(1 - \varepsilon_j)$

Calculation of final post-season density: $N = P_j N_{potential}$

Essentially crop competitive density can be calculated as a weighted average of P_j over the time interval $[t_{CREM}, t_{COMP}]$:

$$\widetilde{P} = \sum_{j=1}^{m} \overline{P}_j \widetilde{w}_j$$

where $\overline{P}_j$ is the average value of P in the interval $[t_{j-1}, t_j]$. FIGURE 7.8 shows an example of E_j and P_j over a given season and helps to illustrate the reasoning behind the algorithm. The figure shows the following events occurring at time steps 0 through 5:

Time Step	Event
0	WDEM
1	B_SA
2	E_SA
3	EMTH
4	POST

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For the event at time t_0, weed emergence for species i has just begun, so $\overline{P}_j = 0$, and so:

$$\widetilde{P}_0 = \overline{P}_0 \widetilde{w}_1 = 0$$

For time t_1, the application of a soil-applied herbicide has occurred, but the calculation of $\overline{P}_j$ involves the average of densities in the previous interval $[t_0, t_1]$. Since the population at t_0 is zero, this is equal to half the emerged density at time t_1:

$$\widetilde{P}_1 = \widetilde{P}_0 + \overline{P}_1 \widetilde{w}_1 = \frac{1}{2} E_1 \widetilde{w}_1$$

For time t_2 the period of activity of the soil-applied herbicide has fully elapsed. For this interval $[t_1, t_2]$ the average density $\overline{P}_2$ is approximated as the following:

$$\overline{P}_2 = P_1 + \frac{1}{2}(E_2 - E_1)(1 - \varepsilon_H)$$

where ε_H is the efficacy of the soil-applied herbicide applied to the newly emerging cohorts in the present time interval. Thus,

$$\widetilde{P}_2 = \widetilde{P}_1 + \overline{P}_2 \widetilde{w}_1 = \widetilde{P}_1 + \left[P_1 + \frac{1}{2}(E_2 - E_1)(1 - \varepsilon_H) \right] \widetilde{w}_2$$

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For time t_3 end-of-month reporting (EMTH) is occurring, and no weed control is occurring or has occurred in the time interval $[t_2, t_3]$. Thus, $\overline{P}_3$ is approximated again as follows:

$$\overline{P}_3 = P_2 + \frac{1}{2}(E_3 - E_2)$$

and:

$$\widetilde{P}_3 = \widetilde{P}_2 + \left[P_2 + \frac{1}{2}(E_3 - E_2) \right] \widetilde{w}_3$$

For time t_4 a post-emergence weed control event has occurred, but its occurrence at time t_4 does not affect the average weed density in the time interval $[t_3, t_4]$. Thus, this is treated identically as in the previous time interval:

$$\widetilde{P}_4 = \widetilde{P}_3 + \left[P_3 + \frac{1}{2}(E_4 - E_3) \right] \widetilde{w}_4$$

Lastly, time t_5 is initiated by another end-of-month reporting event, where no control is presently occurring. A post-emergence control event has occurred at the beginning of the time interval $[t_4, t_5]$, but the effects of this are implicit in the value of P_4. Thus, the equation is of the same format as in the previous interval:

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$$\widetilde{P}_5 = \widetilde{P}_4 + \left[P_4 + \frac{1}{2}(E_5 - E_4) \right] \widetilde{w}_5$$

Thus, the algorithm for calculating crop competitive density can be effectively summarized as follows:

Beginning of weed emergence: $\widetilde{P}_j = 0$

Events where no soil-applied herbicide

control is occurring: $\widetilde{P}_j = \widetilde{P}_{j-1} + \left[P_{j-1} + \frac{1}{2}(E_j - E_{j-1}) \right] \widetilde{w}_j$

Control via a soil-applied herbicide: $\widetilde{P}_j = \widetilde{P}_{j-1} + \left[P_{j-1} + \frac{1}{2}(E_j - E_{j-1})(1 - \varepsilon_j) \right] \widetilde{w}_j$

Calculation of final post-season density: $\widetilde{N} = \widetilde{P}_j N_{potential}$

where $\widetilde{w}_j$ is the weighting function at time j:

$$0 \leq \widetilde{w}_j \leq 1$$

and $\widetilde{P}_j$ and $\widetilde{N}$ are respectively analogous to P_j and N but for crop competitive density.

For a detailed programmatic description of the implementation of crop competitive density into the WISDEM model code the reader is referred to Appendix E.

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7.3 Emergence Curve Re-Parameterization

In addition to the algorithmic modifications described previously, there was some question raised as to the realistic validity of the emergence curves as they were presently parameterized. More specifically, it appeared early on that in particular the emergence curves were too wide, spreading the timing of emergence over too long a time period and creating an unrealistically large proportion of late-emerging cohorts. FIGURE 7.9 from Hartzler and Buhler (1997) shows some of the information that was qualitatively interpreted into an approximate re-parameterization of the emergence curves.

There are three parameters involved in the parameterization of the emergence curve for a given weed species:

$$p(t_w) = \frac{\beta}{\eta}\left(\frac{t_w - \gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t_w-\gamma}{\eta}\right)^{\beta}}$$

These parameters are:

β: Parameter controlling the general shape of the emergence curve (skewness, etc.)

η: Parameter controlling the length of time emergence occurs

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γ: Time in season when emergence begins

and the distribution described in the above equation is known as a Weibull distribution. For simplicity, the shape parameter β was set to the same value for all such parameterizations:

$$\beta = 2$$

This value is reasonably close to most values from previous parameterizations, and it gives the emergence curves a slight skewness to the right that allows for some emergence cohorts late in the season. With the shape parameter set to this constant, the remaining parameterizations simply controlled when emergence would begin and a characteristic time in which it would elapse.

Much of the parameterization information also came from an online emergence poster created by Hartzler et al. (2000), where various weed species were categorized into groups.

7.4 Sensitivity Analyses

FIGURE 7.10 shows the results of two model runs in WISDEM, both of which involved continuous corn planted each year on 1 May, and harvested on 1 November.

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The results are shown for densities of barnyardgrass. No control measures were included in the model run, so the weed densities indicate a logistic approach to a carrying capacity. What is noteworthy here is the lower capacity associated with the model run with fecundity reduction turned on.

FIGURE 7.11 shows four graphs with each graph showing the results for a set of seven model runs. The runs were all done for common lambsquarters in continuous corn with the same planting and harvest dates described before. In each year two applications of Roundup Ultra™ were simulated to occur at 30 April and 20 May. The seven runs were performed with the efficacy of this herbicide set to seven different percentages shown in the graph legend. Graphs in the left column show results with fecundity reduction turned off, and graphs on the right show the same with fecundity reduction turned on. Graphs in the top row show results with the emergence curve parameters set to previous values, and graphs on the bottom row show results with the emergence curve parameters set to new values. The results indicate a greater sensitivity of weed population dynamics to changes in the timing of emergence. This initially provided the hope that WISDEM could serve as an effective simulation model, because it provided the possibility that the model dynamics could effectively be "tuned" to a given set of field conditions by adjusting the emergence curves. It also implies an ecological hypothesis that inasmuch as the model algorithm correctly represents the significant processes that contribute to actual population dynamics, the primary venue in which year-specific environmental events may result in seasonal changes in population dynamics is through effectuating seasonal changes in emergence timing.

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7.5 Initial Validation

A validation procedure was performed comparing model results with the experiments of Wilson (1993), the results of which are displayed in FIGURE 7.12. For this result reproductive density was turned on and the emergence curves were re-parameterized. In an effort to isolate the validation to elements of competition and seed production, this validation focused exclusively on the data from the above study for the control plots, where no control measures were applied. Note that when this figure is compared with FIGURE 7.3 it is suggested that the advent of these two changes has in fact resulted in a reversal of the issue of overestimating low weed densities. This finding in combination with the high sensitivities observed in the previous section suggests that with the additional algorithmic advancements described in this chapter a viable model producing realistic results is now obtainable.

7.6 Internal Software Upgrades

WISDEM was originally written in Microsoft Visual Basic version 5.0 using Data Access Objects (DAO) to interface with databases written in Microsoft Access 97. The process of performing the present work involved the implicit upgrading of the software to Microsoft Visual Basic Professional version 6.0 using ActiveX Data Objects (ADO) to

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interface with databases written in Microsoft Access 2000 or Access XP. In many instances this involved the replacement of obsolete program commands or algorithms with commands and algorithms conforming to this new environment. In each instance such replacements are well-documented within the software code in a fashion that should be easily interpretable to any future programmers. For a full programmatic description of the implementation of ADO in the WISDEM code, the reader is referred to Appendix F.

7.7 Interface Advancements

The understanding was made early on that along with adjustments to the underlying model algorithm similar changes would also need to be made to the software GUI (graphic user interface). Elements of the initial interface are displayed in FIGURES 7.13 through 7.17, with the main interface form displayed in FIGURE 7.13. Clicking on the center button initiated the forms shown in FIGURE 7.14, which allowed for the choosing of weed species and pressures. Returning to the form in FIGURE 7.13, clicking on the button farthest to the right allowed for the creation of a crop rotation guided by the form controls illustrated in FIGURE 7.15. In addition, herbicide and tillage events would also be entered in this same graphical format with the aid of the form illustrated in FIGURE 7.16. Lastly, FIGURE 7.17 shows an example of how the model output could be displayed in a graphical format.

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Although the above interface contained some truly impressive elements, specifically for the next step it was desired that the interface be updated to be more efficient, Windows savvy, and to make a more effective use of graphical space. With this in mind, early work on the WISDEM model focused on the extraction of the underlying model algorithm from its existing interface. This involved a thorough and time-consuming analysis of each software module to determine its specific function in the software. This has resulted in a significant commentation of the model code that should also assist any future programming efforts. In some instances it also resulted in the removal of unused or obsolete procedures. Most significantly, however, it resulted in an extraction of the fundamental model algorithm from the entirety of the software. Thus, a discussion of the recreation of the model interface should begin with a description of some noteworthy elements of this underlying algorithm.

The model algorithm communicates with three database files, two of which are named by the user. With the user choosing a name of "myrun" the three files are named as follows:

myrun.mdb

myrunout.mdb

param.mdb

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The first two files respectively store input and output information for the present run. Model parameters (competition, emergence, etc.) are stored in param.mdb. Specifically the model reads information from the following tables in myrun.mdb:

CROPDAT	Crop planting and harvest events
HERBDAT	Herbicide application events
MUNAME	Names of management units
TILLDAT	Tillage events
WEEDDAT	Weed species present and densities

For the CROPDAT, HERBDAT, and TILLDAT tables one record is stored for each event in the simulation. Thus, for example, if three applications of Roundup Ultra™ are made each year and the simulation is being run for ten years, then there will be 30 records in the HERBDAT table to cover these 30 events. For the CROPDAT table two records are created for each cropping season, one for the planting event and the other for the harvest event. Thus, a twenty-year simulation in WISDEM with no fallow years will have 40 records in CROPDAT. The WEEDDAT table contains one record for each weed species present. In each of the aforementioned tables a field exists that gives a number for a specific management unit. In the MUNAME table the names of each of these management units are stored.

A model run is initiated via the RunModel procedure in the modOverall module.

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The results of a model run are written to the myrunout.mdb file which contains four tables:

GPFYLDLOSS	Percentage yield loss for each cropping season
MONTHPRESS	Densities of each weed species at the end of every month in the simulation
WEEDCROP	Densities of each weed species at the time of crop harvest
WEEDPOP	Densities of each weed species at the time of weed senescence

In the GPFYLDLOSS table one record is created for each cropping season. In the WEEDCROP and WEEDPOP tables one record is created for each weed species and each harvest date and date of weed senescence, respectively. The MONTHPRESS table stores one record for each weed species and each month in the simulation.

Thus, an appropriate interface of the above algorithm is one which would allow for an implementation of the above algorithm in a format that would allow for multiple management units, multiple farms, multiple users, and potentially multiple geographic locations. With this in mind, the concepts of "profiles" and "runs" were created.

A "run" is, simply, a set of one or more management units for which a simulation is desired. Crop consultants who would like to keep a simulation record for each of their clients would probably have each grower represented by a single "run".

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A "profile" defines a set of demographic parameters for a given set of "runs". Many consultants in the western Great Plains would want to have at least two profiles, one for all of her irrigated clients and the other for all of her dryland clients. As WISDEM grows and its usage becomes more widespread, additional settings may be attached to a given profile that would allow for the selection of the competition and emergence parameters specific to a given geographic region.

When a user first enters the software, she sees a maximized MDI parent form (FIGURE 7.18) with the first of three MDI child forms allowing for the selection of a profile and then a run (FIGURE 7.19). After these are selected this Profile form is moved from the center of the screen to the lower left and appears behind the Simulation Information form (FIGURE 7.20). On this form all information for running a simulation is entered, beginning with a definition of management units. At least one management unit has to be defined for each run, and such is done in the upper left, where the name of a management unit is entered in the input text line farthest to the upper left and the nearby right arrow button is clicked. The name of the management unit then appears in the list box to the right, and if the user clicks it, then its settings appear in the remainder of the form. First, in the sections to the right the user can indicate the rotation length and the number of years to simulate. For example, a corn/soybeans rotation would have a rotation length of 2 years. A wheat/corn/fallow rotation would have a simulation length of 3 years, and so on. A continuous cropping situation would have a simulation length of 1 year.

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Next the user can enter the crop rotation for this management unit. Each crop in the rotation is entered individually. For example, in a corn/soybeans rotation the user would first choose corn from the crop list and would enter appropriate planting and harvest dates for the first year of the rotation. After checking to insure that the rotation length was set to 2 years the user would click on the nearby right arrow button and the planned seasons of corn would appear in the crop rotation list box in every other year from the year indicated in the entered plant and harvest dates forward for however many years are indicated by the number of years to simulate.

Next the user would choose settings for the soybeans. Soybeans would be chosen from the crop list, and planting and harvest dates would be chosen in the appropriate boxes. Here when choosing planting and harvest dates the user would be careful to choose the year after the first year of planting corn and would click the nearby right arrow button. The settings for the soybean years of the simulation would be observed in the crop rotation list box. For either case a small text box located immediately to the right of the crop list box allows the user to specify a seeding rate in pounds per acre, but this is optional, as a default seeding rate is utilized in its absence.

If one of the crops in the rotation needs to be deleted, such can be done by selecting any of the entries of the crop in the crop rotation list box and clicking the Delete button to the right. Settings for a given crop in the rotation can be changed by selecting the crop in the crop rotation list box and clicking the Change button. In either instance

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the crop will no longer appear in the crop rotation list box, but when clicking the Change button its settings will reappear in the controls to the left, where the user can modify them and click the right arrow button again.

Fallow years require no entry of information in the crop rotation list box.

Below the crop production section of the form is a section for indicating weed species present along with initial potential densities for each species. The species is chosen from a weed species list, and weed densities can either be chosen from a list of seven possible densities, or they can be entered explicitly in a small text box to the right. Densities are indicated in plants per square meter. After settings for a given species are entered, clicking on the nearby right arrow button places the weed on the weed species list box to the right. Here the Delete and Change buttons have the same function as in the crop rotation section.

Next the user can select herbicides and application dates using controls that function in the same fashion as before. Note that in the above example with the corn/soybeans rotation if the same herbicide is used in both the corn and the soybeans it will need to be entered twice, once for the first corn year and the other for the first soybean year. Multiple herbicide applications in the same year can be entered, but to insure that they are properly replicated throughout the simulation time period they should be spaced at least two days apart.

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Lastly, tillage events can also be entered in the same fashion as before.

Clicking on the Run button initiates the simulation, the results of which are shown in another form that appears. This is the Simulation Results form (FIGURE 7.21), where weed densities are displayed in a list in the top half, and simulation events are displayed in the lower half.

In particular with regards to this Results form it is hoped that the Syngenta programming team will feel free to enhance the user-friendliness of this data display. Indeed this invitation extends to the fullness of the interface, as this interface was only intended as a temporary interface for performing all model runs necessary for improving the underlying algorithm.

From this point settings in the "Simulation Information" form can be changed and the run can be re-simulated with the results appearing again in the "Results" form. In an effort to avoid confusion as to which settings are associated with a given model result, all results are erased when a setting in the "Simulation Information" form is modified.

The interface also organizes user information in two places. The paramdb.mdb file is located in the Data subfolder located in the software's folder entry in the Program Files folder. In addition, a Profiles.mdb file in the same location tracks settings for each profile.

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The second location is in a "Wisdem Files" folder that is created as a subdirectory of the user's "My Documents" folder (FIGURE 7.22). Here each profile is stored as a subfolder of "Wisdem Files" with two folders "In" and "Out" placed inside of that. All runs for that given profile are stored as individual "mdb" files in the "In" subfolder. Each file in the "In" subfolder contains input settings for the associated run. Output results are stored in a corresponding file in the "Out" folder. The name of this file is equal to the name of the corresponding file in the "In" folder followed by the letters "o", "u", and "t".

FIGURE 7.23 shows the contents of the run file in the "In" subdirectory of a given profile folder. Note the presence of multiple database tables, many of which have been described earlier. FIGURE 7.24 shows example data for three relatively simple tables. The "CROPDATSR" table is just like the "CROPDAT" table except that it only contains the crop rotation information entered directly by the user – i.e., the first rotational occurrence of each crop (FIGURE 7.25). The interface is then responsible for maintaining this information as well as extending it forward throughout the simulation time period and placing all such occurrences in the "CROPDAT" table. The "HERBDATSR" and "TILLDATSR" tables (FIGURE 7.26) have an analogous function, and the interface is similarly responsible for their maintenance and extension, resulting in the population of the "HERBDAT" and "TILLDAT" tables.

The model results are stored in an associated file in the "Out" subdirectory. FIGURES 7.27 through 7.31 show the tables which make up this database file, all of which have been discussed previously.

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On a programmatic level, the following modules are utilized by the underlying model algorithm:

modDatamgt	Database Administration
modEvents	Execution of Modeled Crop Production Sequence
modInit	Creation of Modeled Crop Production Sequence
modLog	Professional Log of Major Code Changes
modMessages	Standardized Library of Information and Error Messages
modOverall	Main Module for Simulation Execution

The following Visual Basic elements are utilized as part of the present interface:

frmAddCrop	Form for Adding a New Crop
frmAddHerbicide	Form for Adding a New Herbicide
frmCalendar	Calendar Interface Form for Entering Dates
frmCropInfo	Crop Information Administrative Form
frmHerbicideInfo	Herbicide Information Administrative Form
frmMain	Simulation Information Form
frmMDIParent	MDI Parent Form
frmOneMomentPlease	Form That Appears When Administrative Forms are Busy
frmProfiles	Profile Form
frmResults	Simulation Results Form

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frmTillageInfo	Tillage Administrative Form
frmWeedInfo	Weed Administrative Form
modInterface	Programmatic Routines for Interface Functionality

The model simulation is initiated by calling the "RunModel" subroutine in the modOverall module.

Lastly, the interface boasts four administrative forms, all of which can be accessed from the "Admin" menu at the top of the MDI parent form. In reference to the ideas of Dharmasri (personal communication) these forms may want to be relegated to an administrative software version.

FIGURE 7.32 shows the first of these forms, a form that maintains all information regarding crops in the model. Demographic information is maintained for the crop via the controls to the left, and on the right side of the form the user indicates the herbicides that are registered for the given crop, where registration is indicated by a checked box.

FIGURE 7.33 shows a similar administrative form for herbicide information, where to the left crop registration information is maintained in a format identical to that of the previous form, and to the right foliar and soil-applied efficacies can be entered and maintained for various weed species.

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FIGURE 7.34 shows a similar administrative form for tillage information, where the two illustrations indicate that either a single efficacy can be specified for all species, or such efficacies can be species-specific.

Lastly, FIGURE 7.35 shows the administrative form for weed information, where demographic parameters can be maintained on the top portion of the form, and herbicide efficacy information can be maintained on the bottom.

7.8 Summary

WISDEM even in its initial state carried with it some strong theoretical advancements. The use of smooth curves for calculating weighting based upon relative timing of emergence combined with the parametric connection between yield loss and weed seed production should prove useful in the future. It is gratifying to witness that with only some relatively minor adjustments some more thorough and satisfying validation exercises appear to be possible. In addition, the sensitivity analysis provides an important ecological implication that environmental dynamics may impact weed population dynamics largely by controlling the timing of emergence for each species.

With the additional enhancements to the interface as well as the programmatic makeup it is hoped that this represents a strong beginning of continued experimentation with this new tool.

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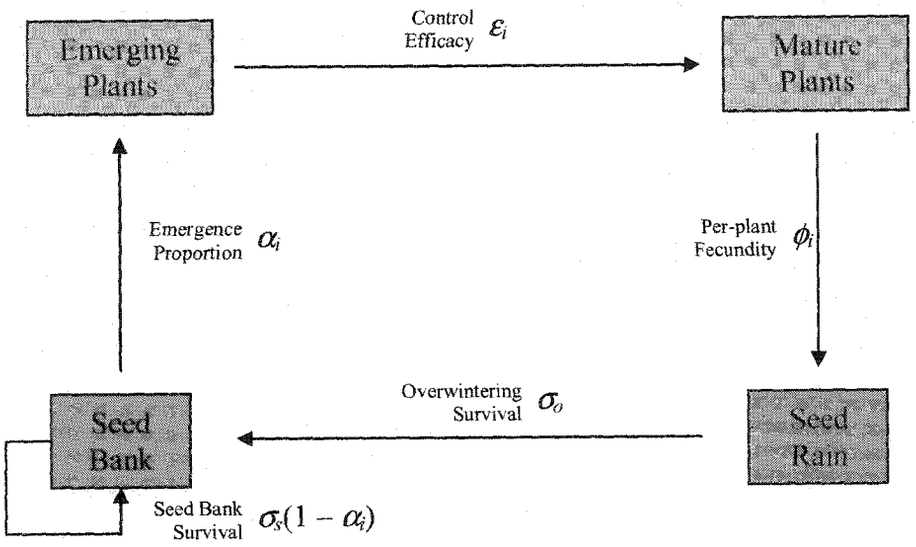

FIGURE 7.1, overall framework of the WISDEM model.

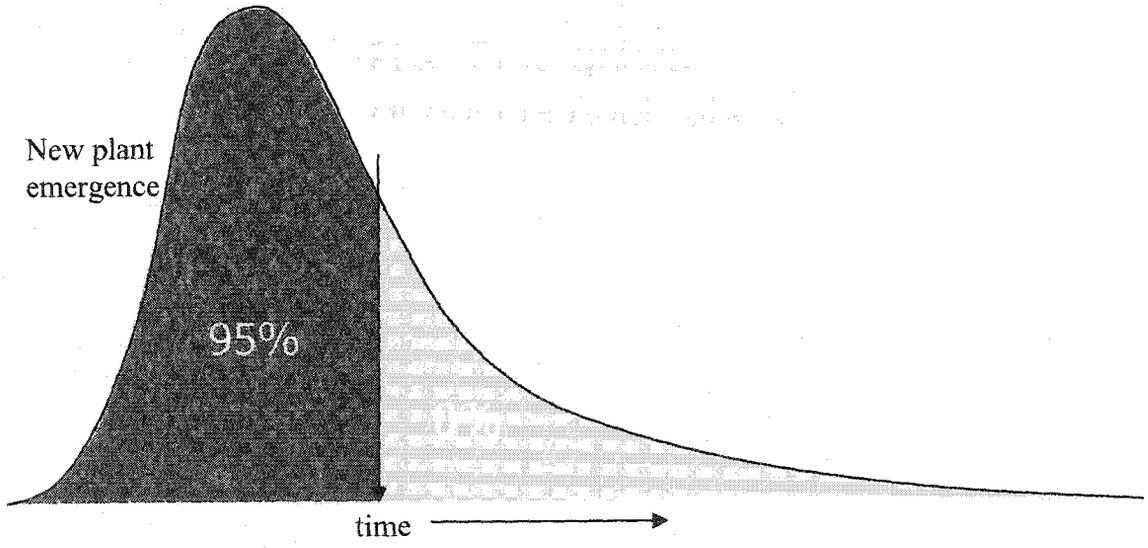

FIGURE 7.2, Weibull emergence curve with effects of post-emergence herbicide application made visible.

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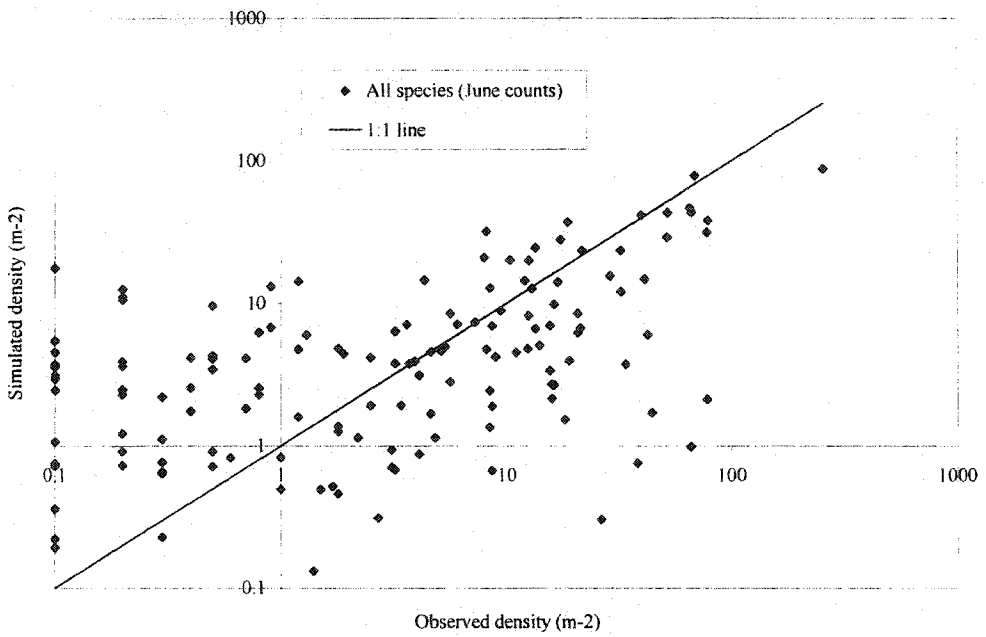

FIGURE 7.3, from Canner et al. (2003), showing validation results for simulations of data from Wilson (1993).

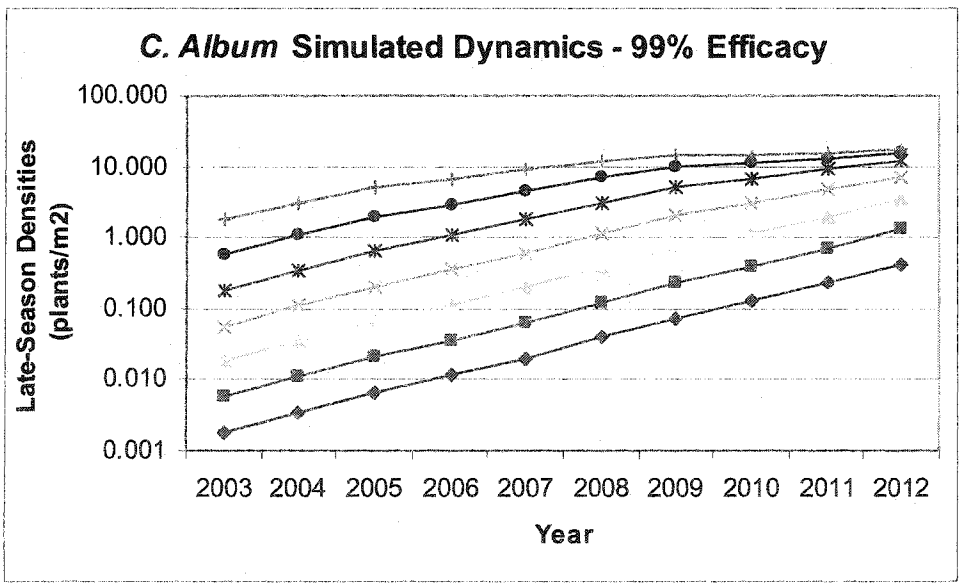

FIGURE 7.4, simulations of growth of common lambsquarters (*Chenopodium album*) in continuous corn with a single application of Roundup Ultra™ applied with a simulated herbicidal efficacy of 99%.

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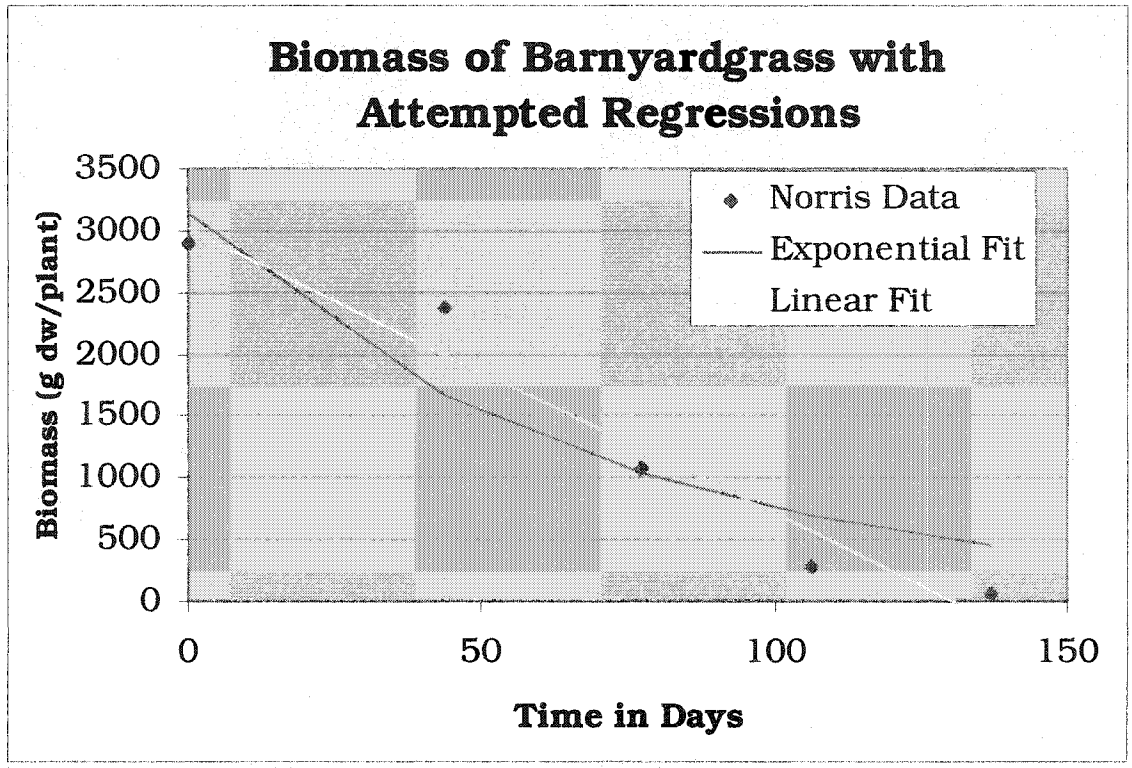

FIGURE 7.5, a pair of regressions done on data from Norris et al. (2001).

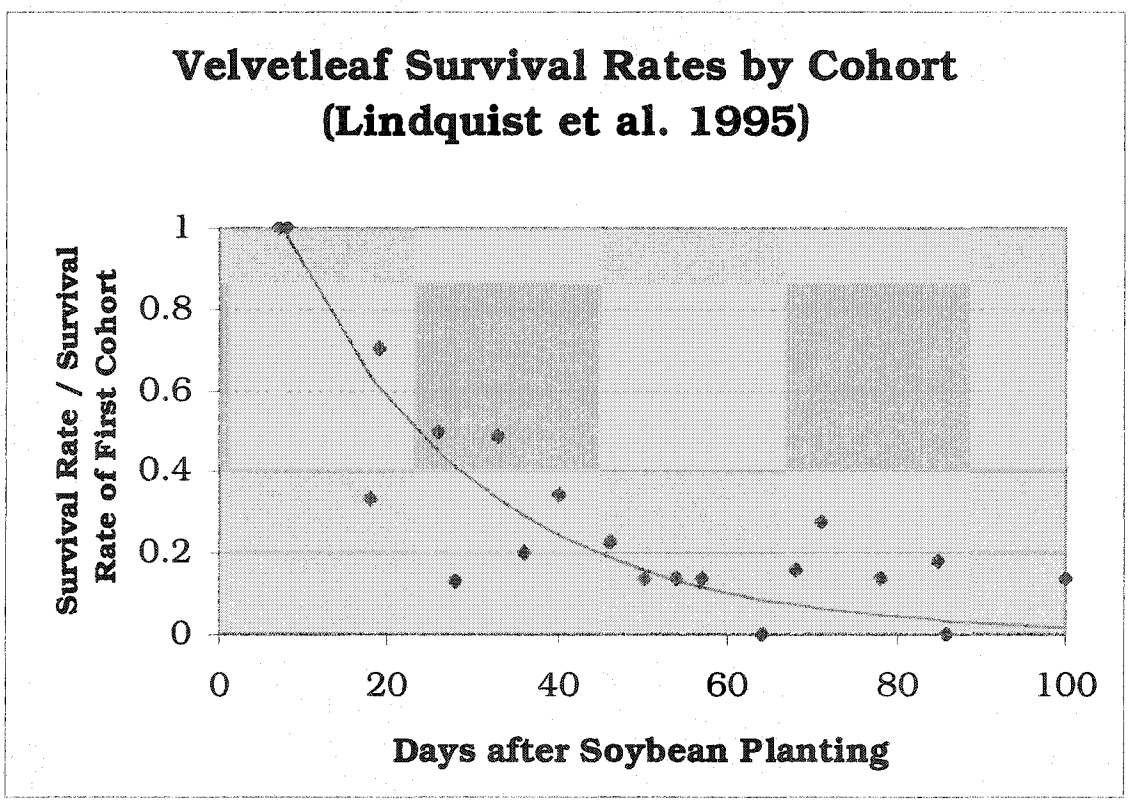

FIGURE 7.6, an exponential regression on data from Lindquist et al. (1995).

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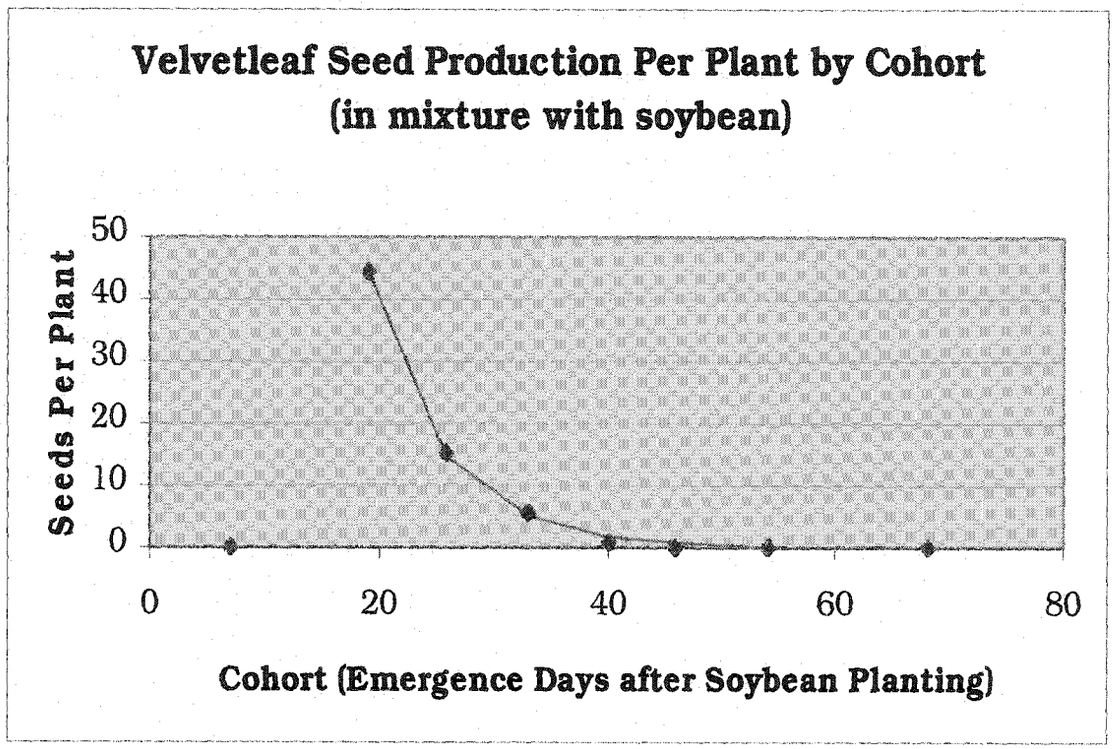

FIGURE 7.7, an exponential regression on additional data from Lindquist et al. (1995). Note the exclusion of an early outlier.

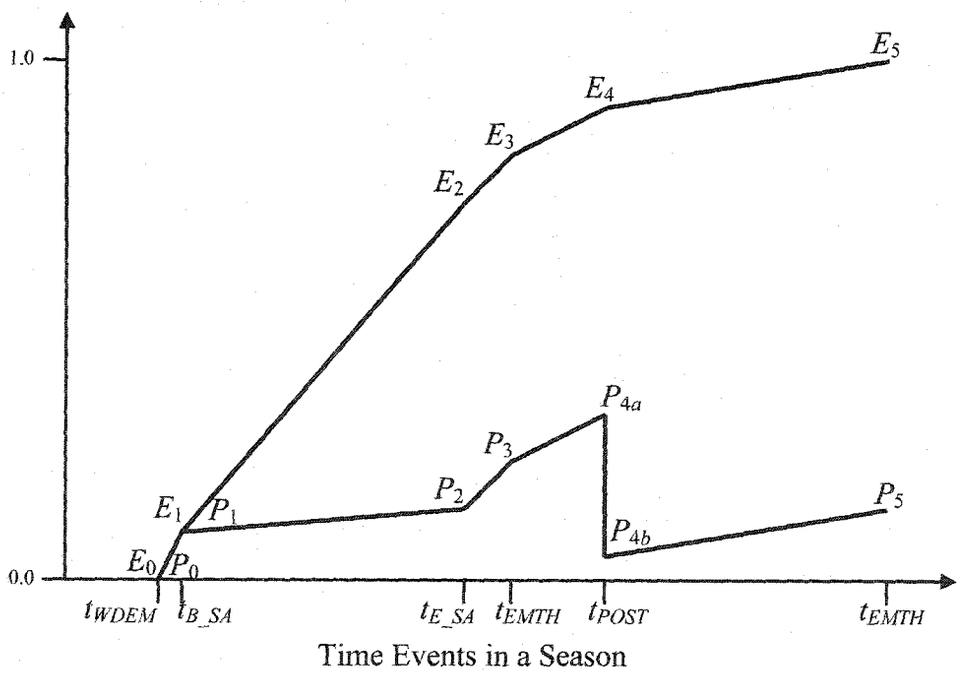

FIGURE 7.8, the evolution of emergence and present proportions (E_j and P_j) in an example set of time events in a single season.

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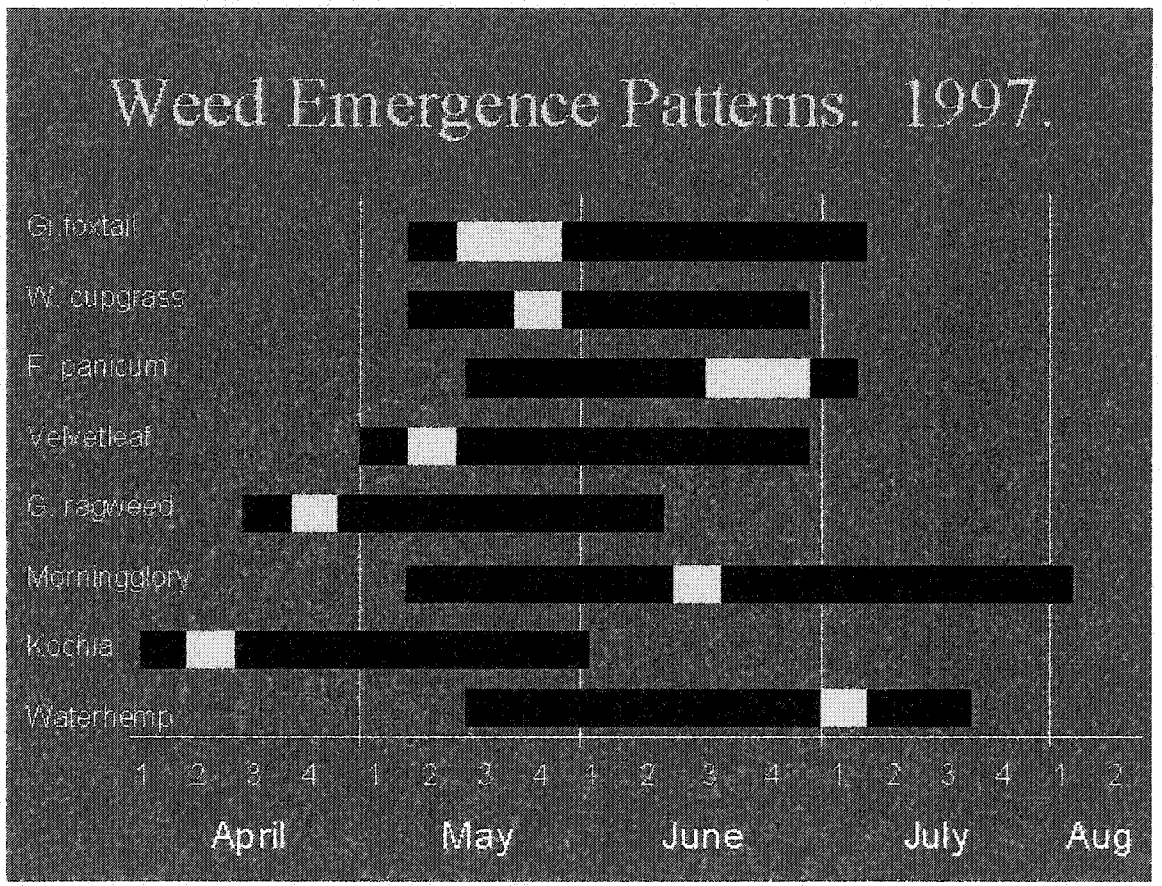

FIGURE 7.9, from Hartzler and Buhler (1997), showing emergence curves for various weed species.

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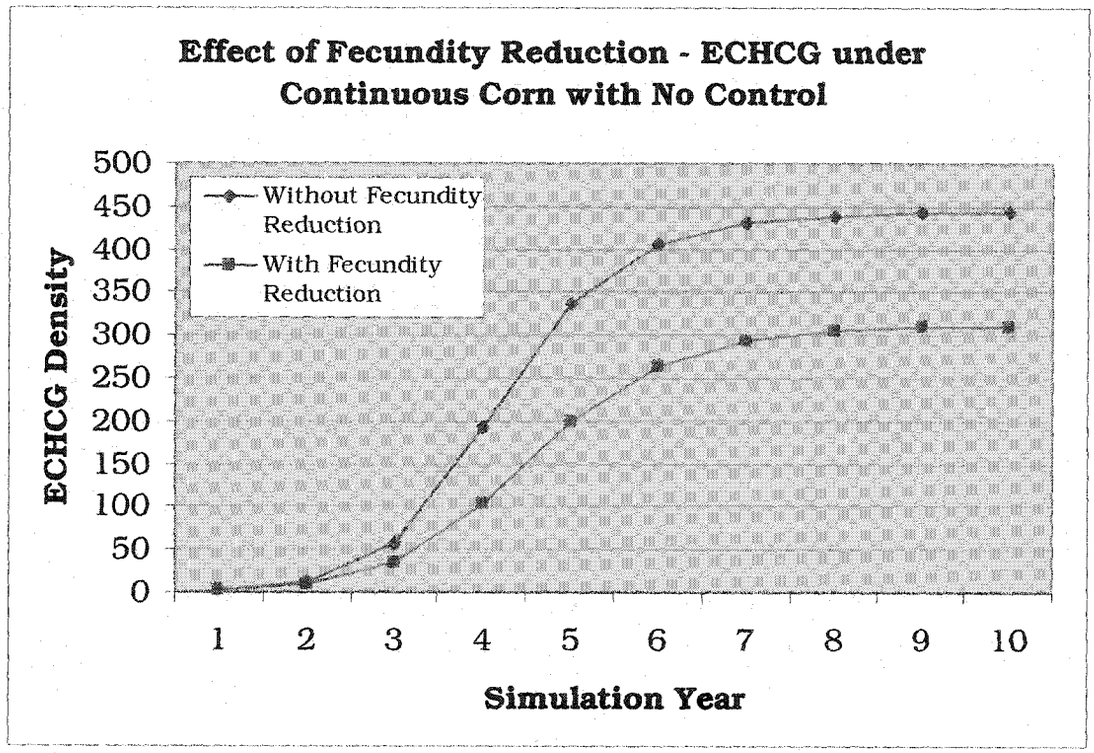

FIGURE 7.10, simulated densities (per square meter) of barnyardgrass in continuous corn with fecundity weighting turned on and off.

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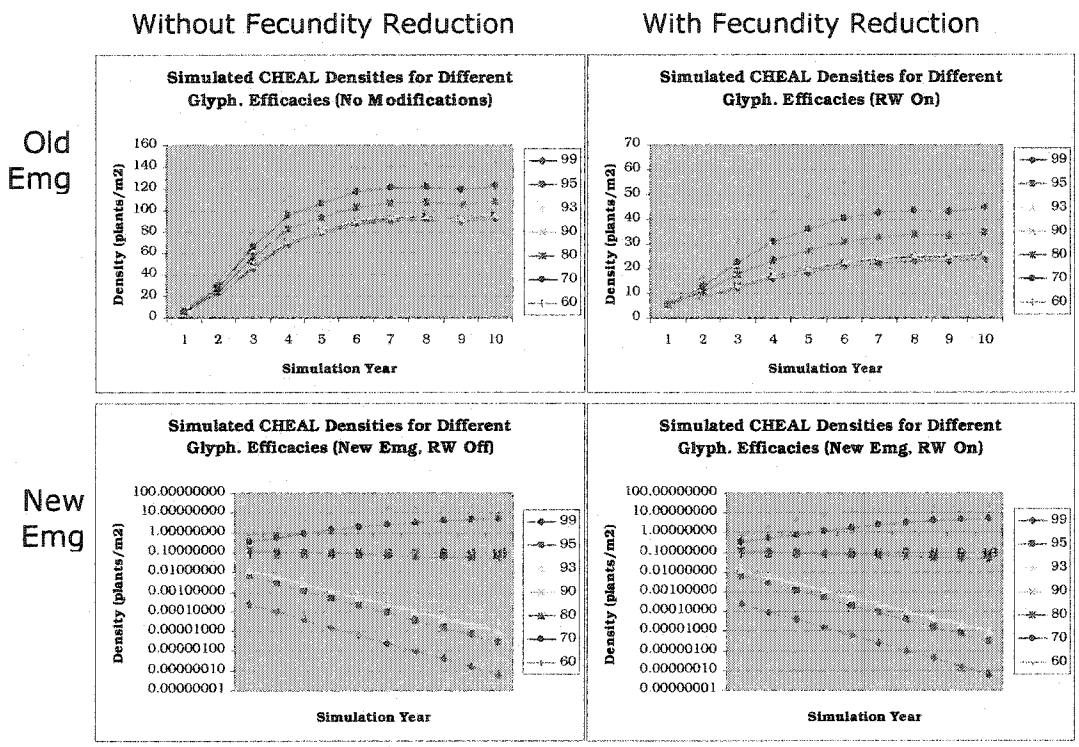

FIGURE 7.11, simulation results for common lambsquarters (*Chenopodium album*) in continuous Roundup Ready™ corn with fecundity reduction turned off and on and emergence curve parameters set to old and new values. Results are shown for seven different efficacies of Roundup Ultra™ applied twice in each season.

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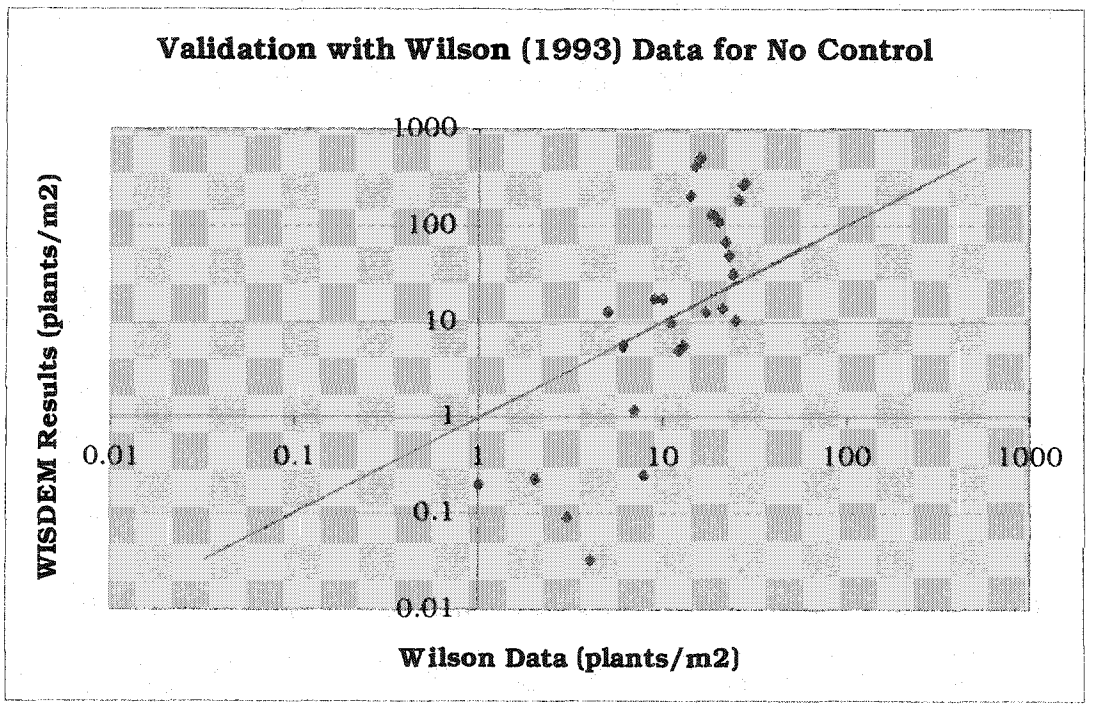

FIGURE 7.12, a comparison between simulated results and results from Wilson (1993). The above results focus on data from the control plots, where no control measures were applied.

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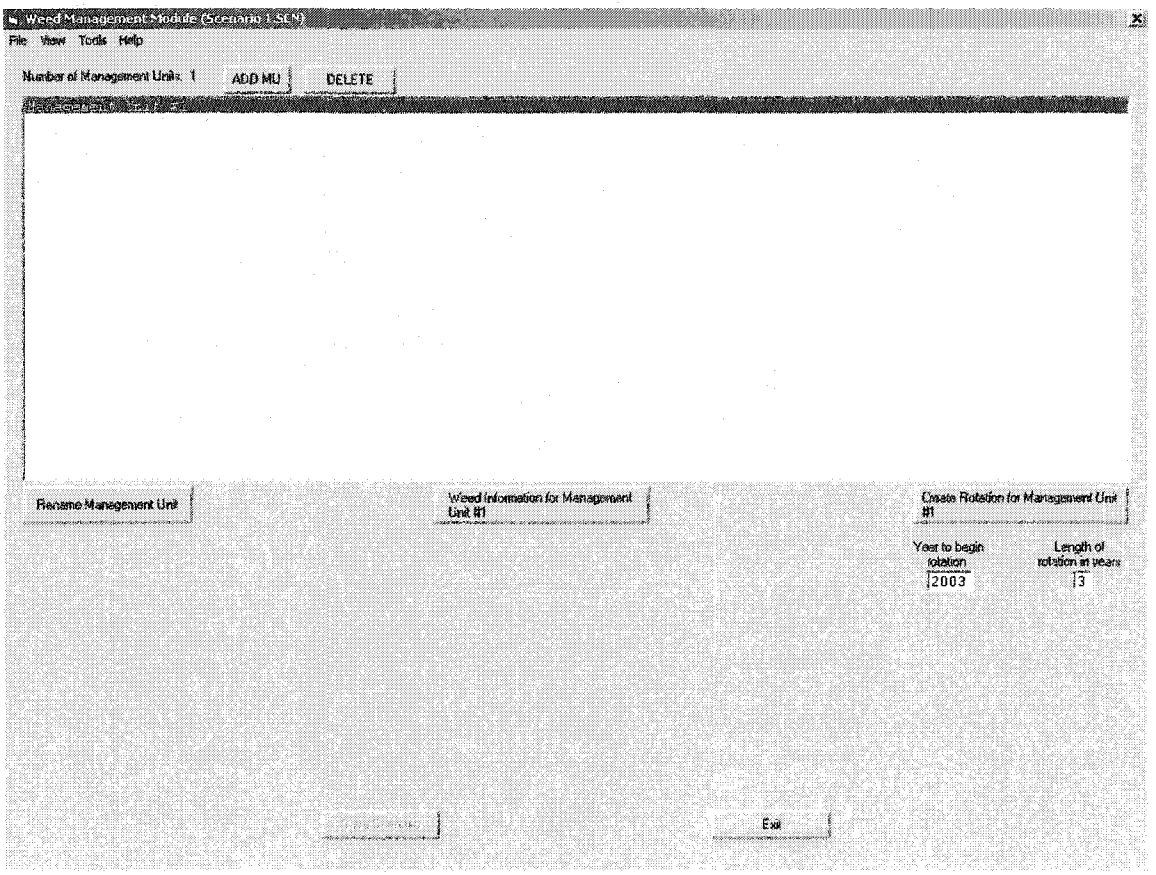

FIGURE 7.13, the main form of the old interface.

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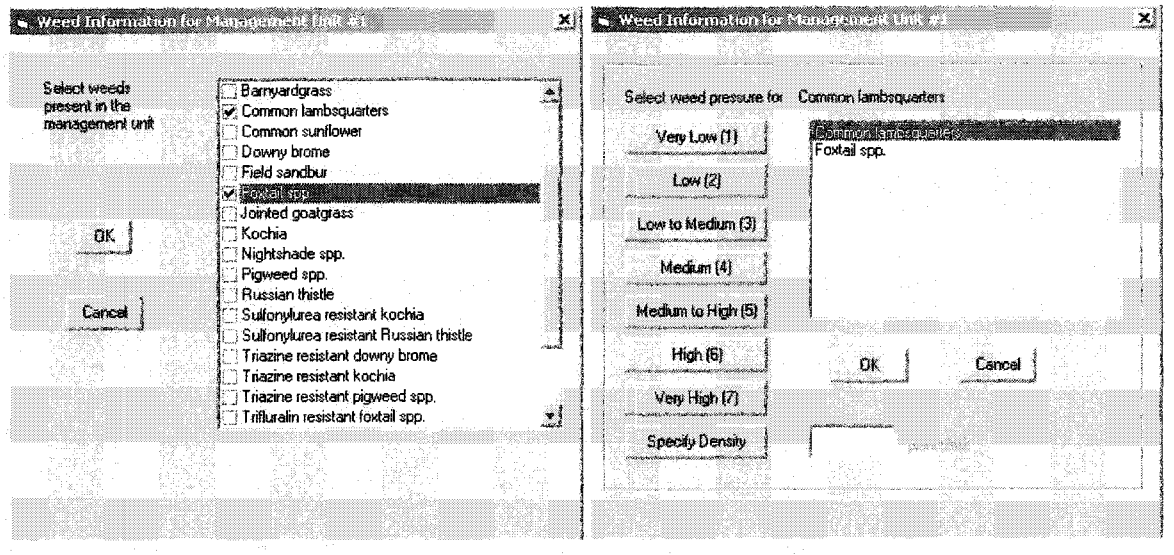

FIGURE 7.14, the form from the old interface for choosing initial weed densities.

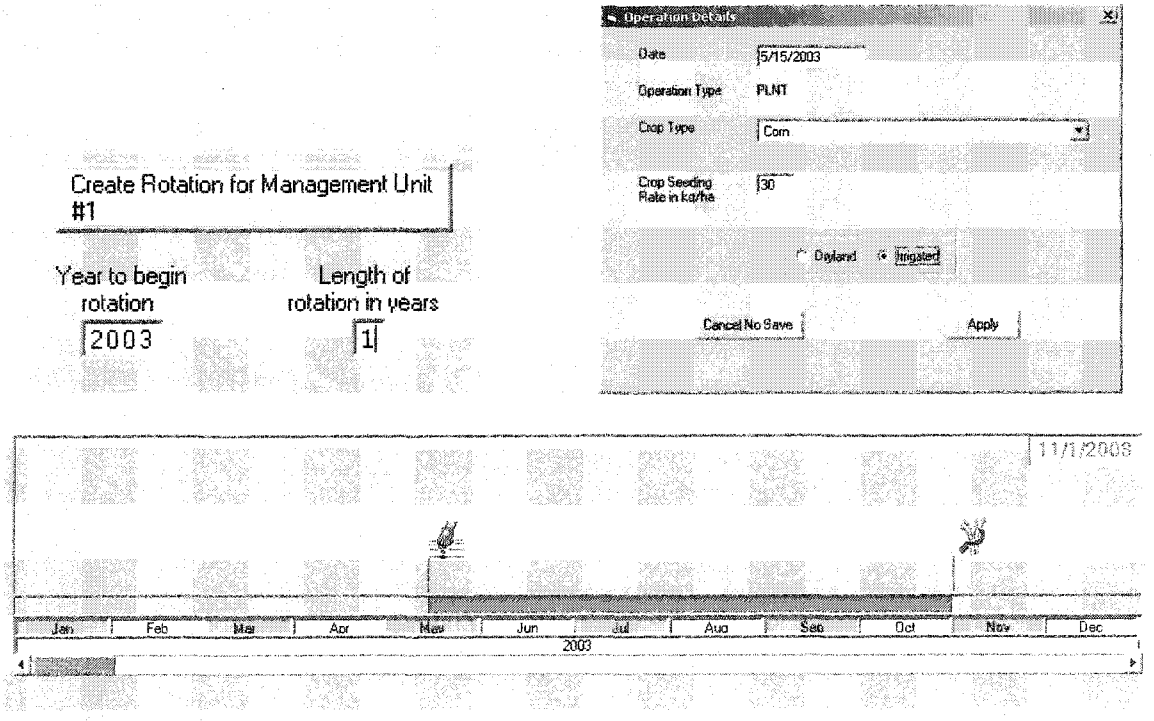

FIGURE 7.15, the form elements from the old interface for choosing a crop rotation.

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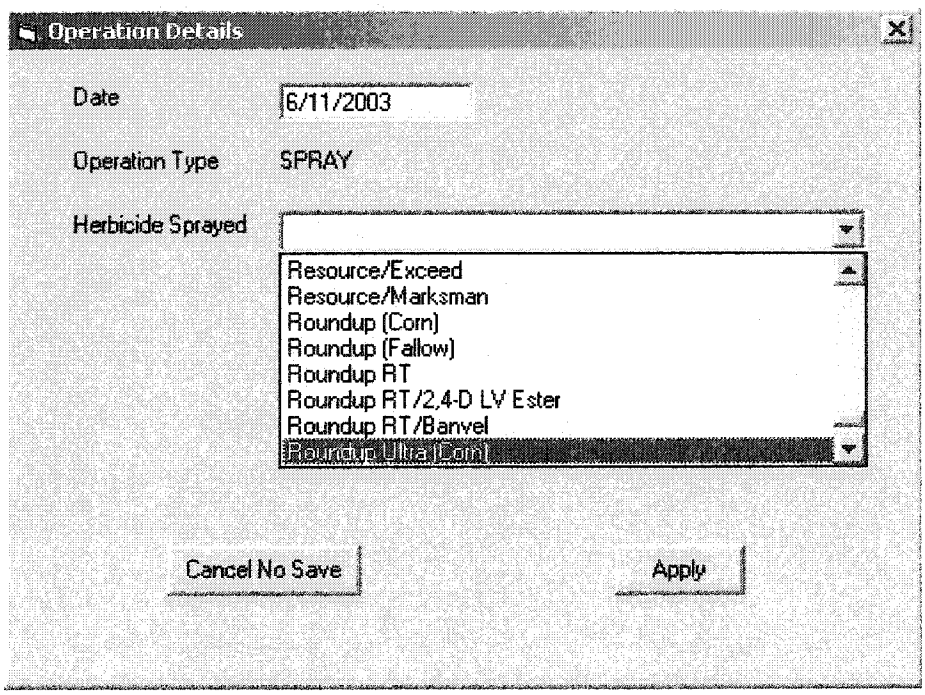

FIGURE 7.16, the form from the old interface for choosing an herbicide application.

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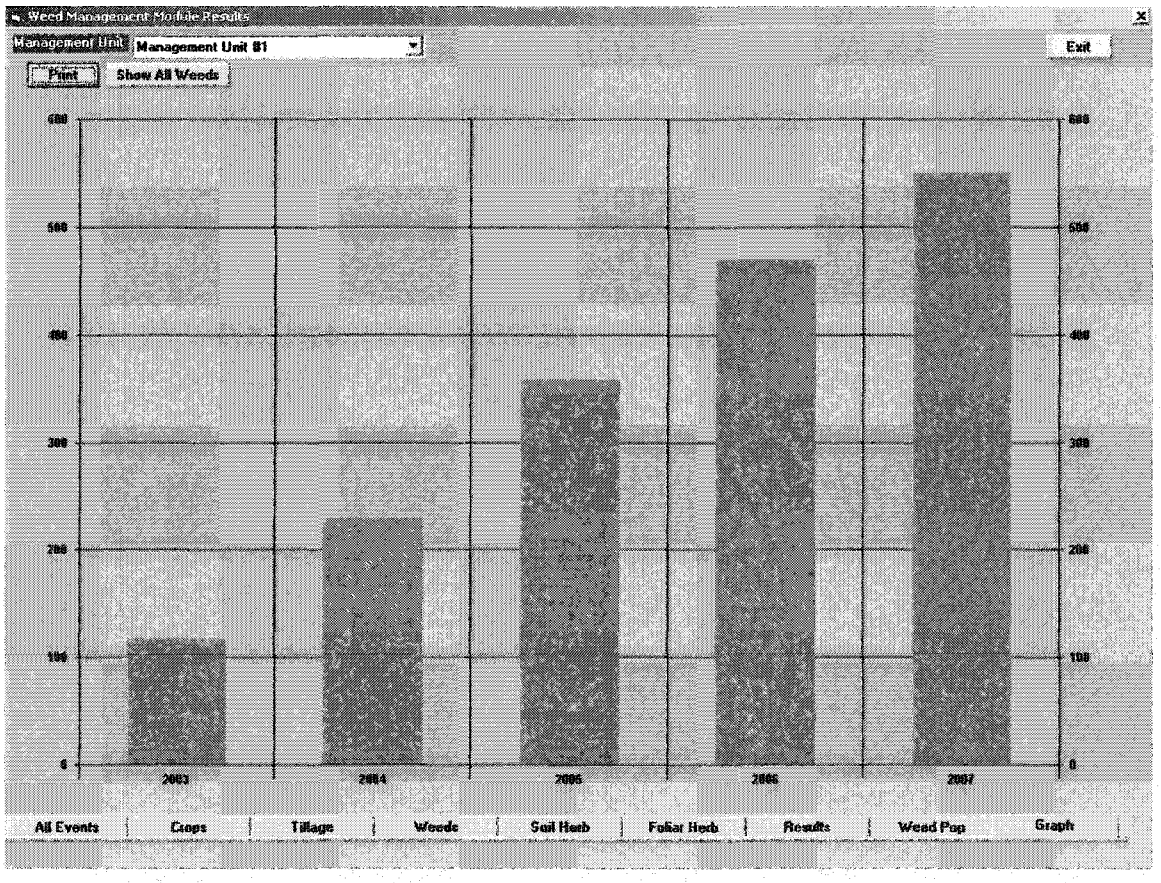

FIGURE 7.17, the graphical output form from the old interface for displaying weed populations over time.

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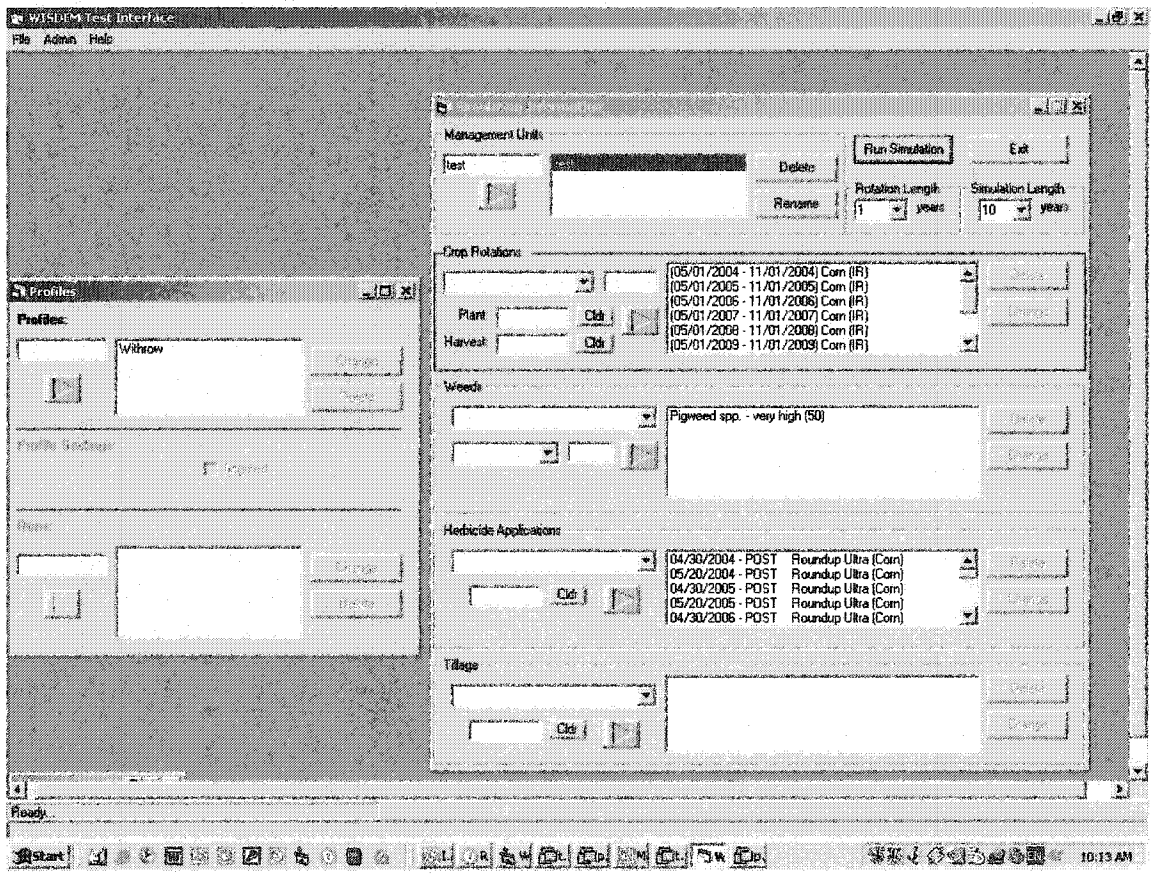

FIGURE 7.18, the new interface with its MDI parent form containing two child forms, the Profile form and the Simulation Information form.

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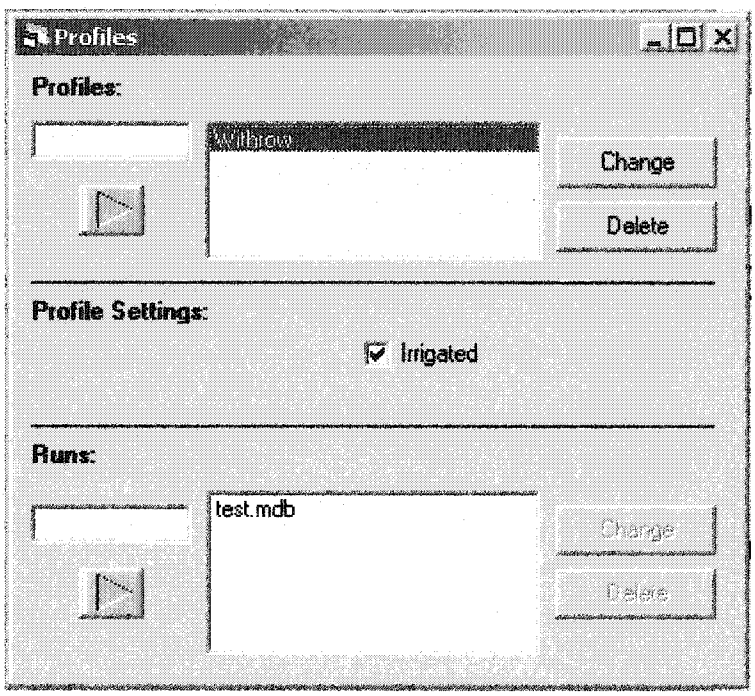

FIGURE 7.19, the Profile form of the new interface.

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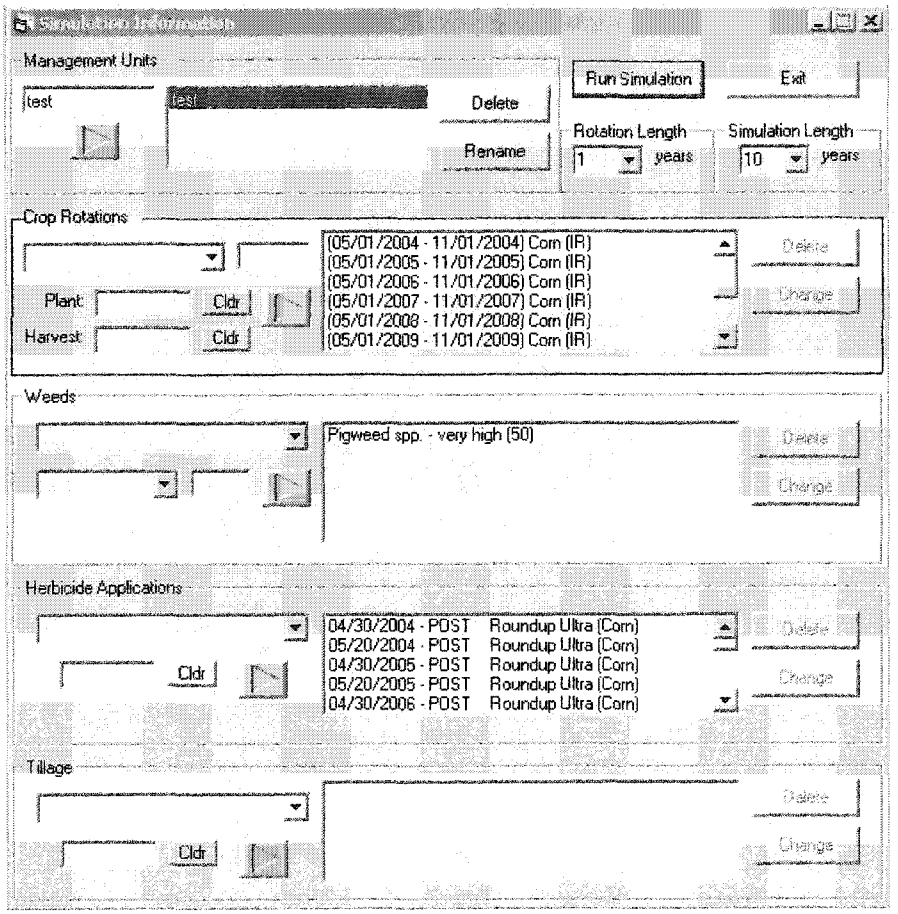

FIGURE 7.20, the Simulation Information form in the new interface.

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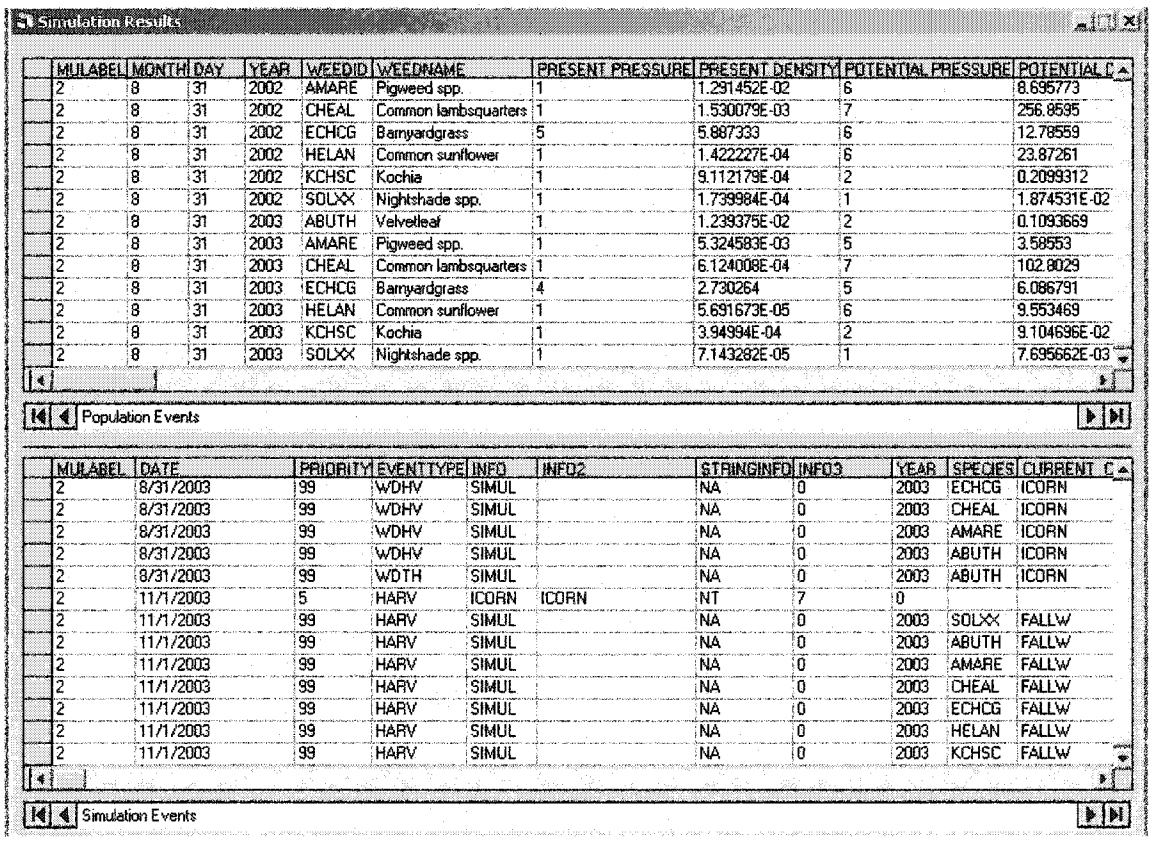

FIGURE 7.21, the Simulation Results form in the new interface.

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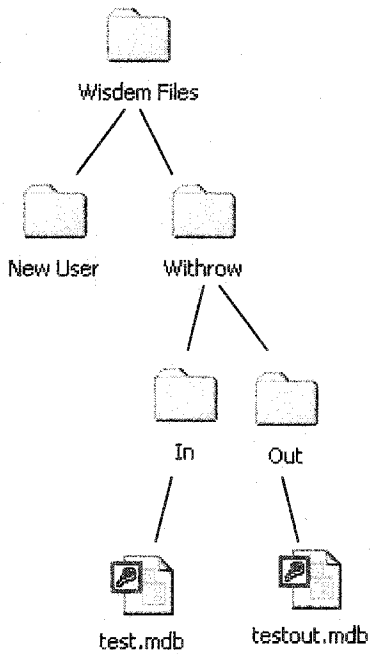

FIGURE 7.22, the structure of the "Wisdem Files" folder in "My Documents".

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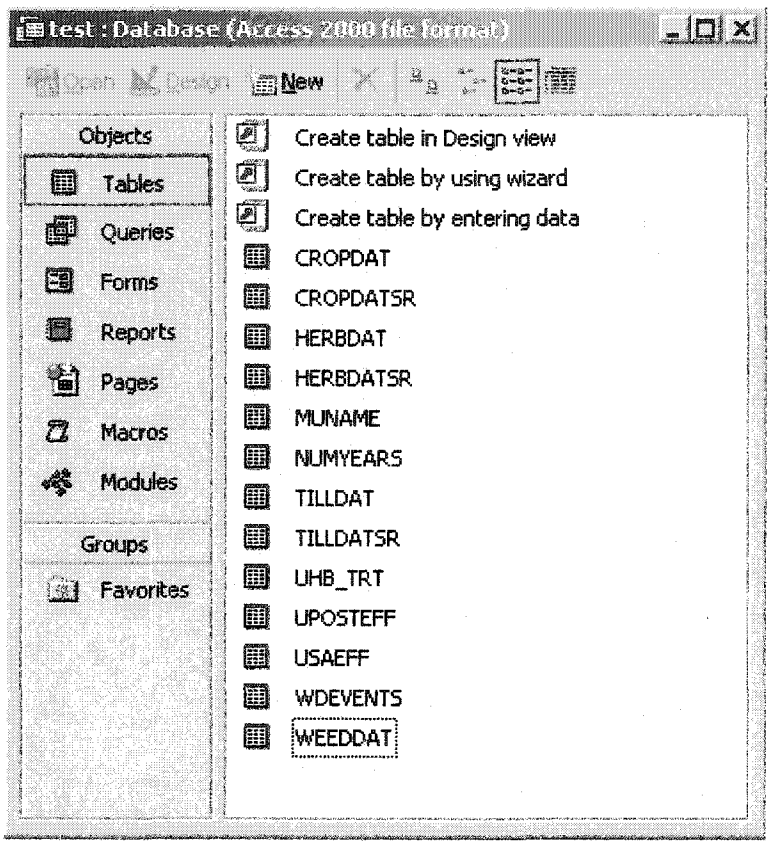

FIGURE 7.23, the tables located in the user input database file.

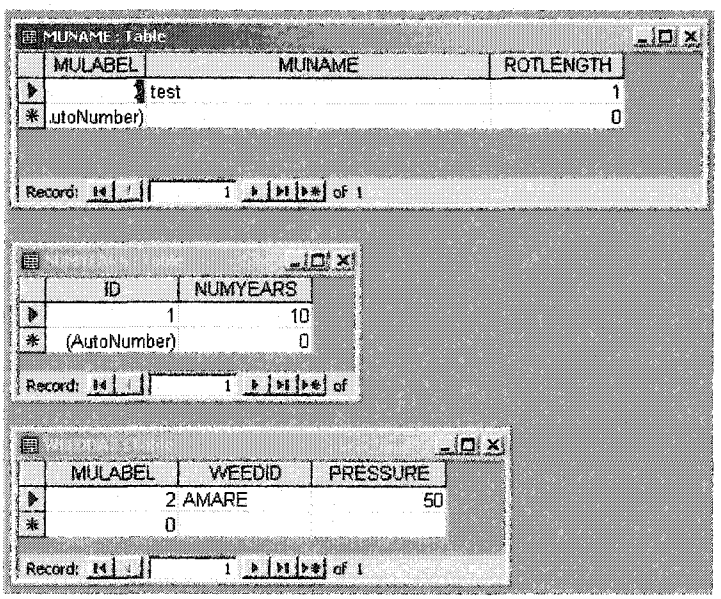

FIGURE 7.24, example contents of the MUNAME, NUMYEARS, and WEEDDAT tables.

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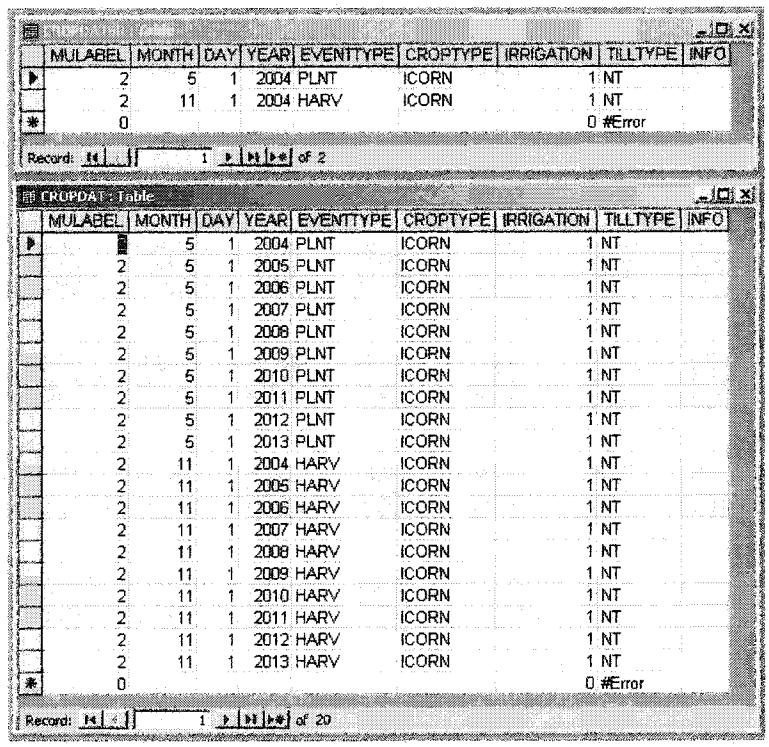

MULABEL	MONTH	DAY	YEAR	EVENTTYPE	CROPTYPE	IRRIGATION	TILLTYPE	INFO
2	5	1	2004	PLNT	ICORN	1	NT	
2	11	1	2004	HARV	ICORN	1	NT	
0						0	#Error	

Record: 1 of 2

CROPDAT : Table

MULABEL	MONTH	DAY	YEAR	EVENTTYPE	CROPTYPE	IRRIGATION	TILLTYPE	INFO
2	5	1	2004	PLNT	ICORN	1	NT	
2	5	1	2005	PLNT	ICORN	1	NT	
2	5	1	2006	PLNT	ICORN	1	NT	
2	5	1	2007	PLNT	ICORN	1	NT	
2	5	1	2008	PLNT	ICORN	1	NT	
2	5	1	2009	PLNT	ICORN	1	NT	
2	5	1	2010	PLNT	ICORN	1	NT	
2	5	1	2011	PLNT	ICORN	1	NT	
2	5	1	2012	PLNT	ICORN	1	NT	
2	5	1	2013	PLNT	ICORN	1	NT	
2	11	1	2004	HARV	ICORN	1	NT	
2	11	1	2005	HARV	ICORN	1	NT	
2	11	1	2006	HARV	ICORN	1	NT	
2	11	1	2007	HARV	ICORN	1	NT	
2	11	1	2008	HARV	ICORN	1	NT	
2	11	1	2009	HARV	ICORN	1	NT	
2	11	1	2010	HARV	ICORN	1	NT	
2	11	1	2011	HARV	ICORN	1	NT	
2	11	1	2012	HARV	ICORN	1	NT	
2	11	1	2013	HARV	ICORN	1	NT	
0						0	#Error	

Record: 1 of 20

FIGURE 7.25, example contents of the CROPDATSR and CROPDAT tables.

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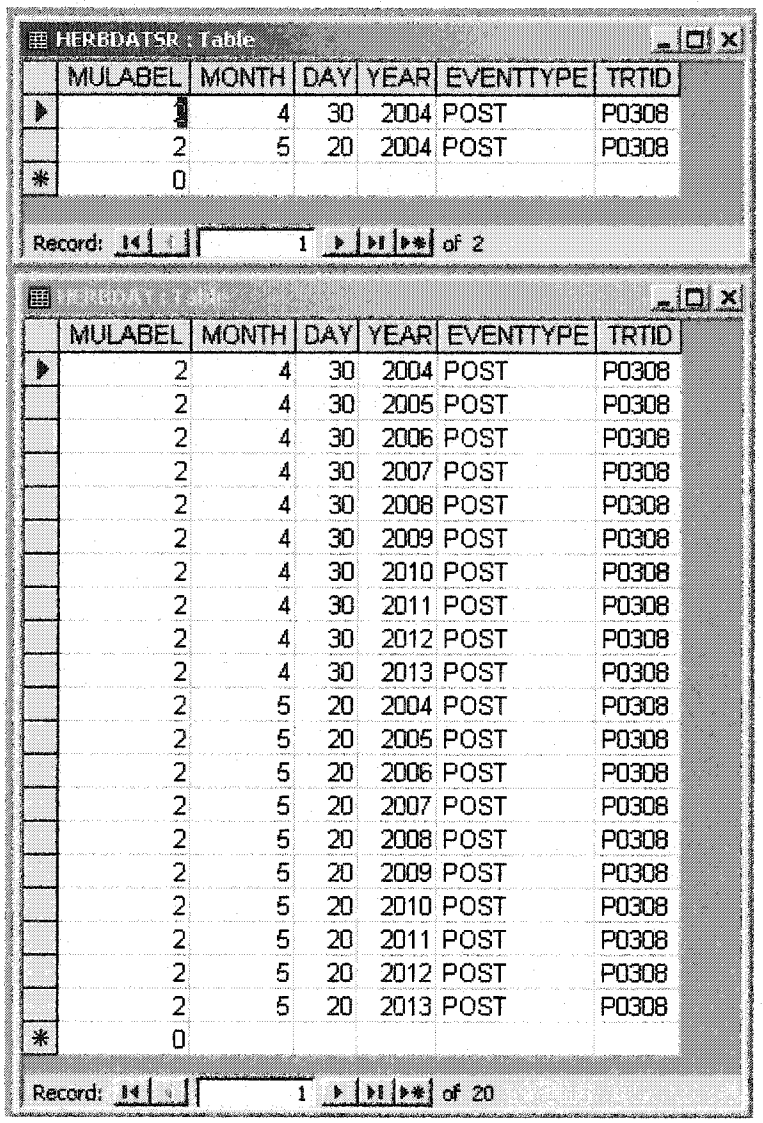

HERBDATSR : Table

MULABEL	MONTH	DAY	YEAR	EVENTTYPE	TRTID
2	4	30	2004	POST	P0308
2	5	20	2004	POST	P0308
0					

Record: 1 of 2

MULABEL	MONTH	DAY	YEAR	EVENTTYPE	TRTID
2	4	30	2004	POST	P0308
2	4	30	2005	POST	P0308
2	4	30	2006	POST	P0308
2	4	30	2007	POST	P0308
2	4	30	2008	POST	P0308
2	4	30	2009	POST	P0308
2	4	30	2010	POST	P0308
2	4	30	2011	POST	P0308
2	4	30	2012	POST	P0308
2	4	30	2013	POST	P0308
2	5	20	2004	POST	P0308
2	5	20	2005	POST	P0308
2	5	20	2006	POST	P0308
2	5	20	2007	POST	P0308
2	5	20	2008	POST	P0308
2	5	20	2009	POST	P0308
2	5	20	2010	POST	P0308
2	5	20	2011	POST	P0308
2	5	20	2012	POST	P0308
2	5	20	2013	POST	P0308
0					

Record: 1 of 20

FIGURE 7.26, example contents of the HERBDATSR and HERBDAT tables.

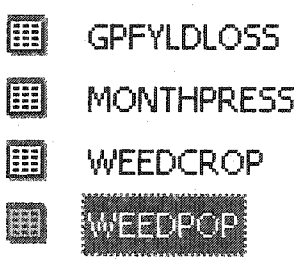

FIGURE 7.27, the tables located in the user output database file.

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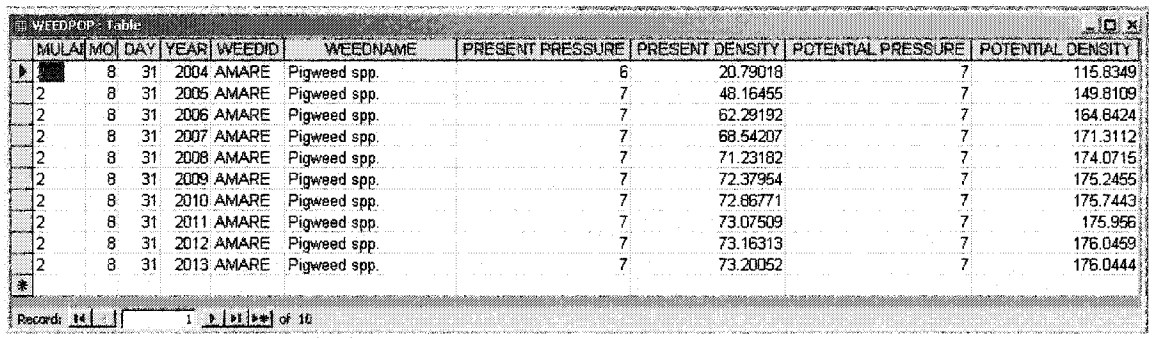
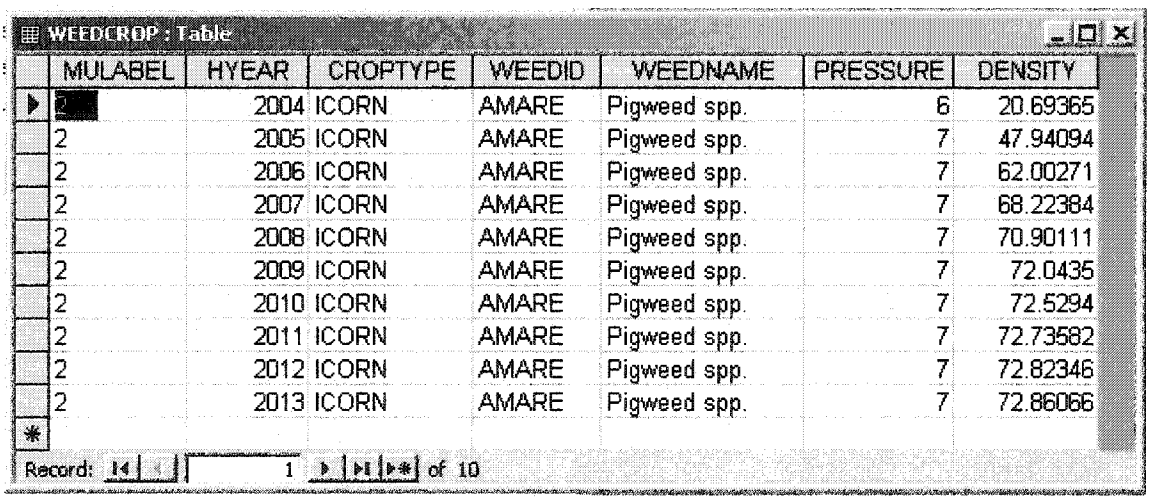


WEEDPOP : Table

MULAB	MO	DAY	YEAR	WEEDID	WEEDNAME	PRESENT PRESSURE	PRESENT DENSITY	POTENTIAL PRESSURE	POTENTIAL DENSITY
2	8	31	2004	AMARE	Pigweed spp.	6	20.79018	7	115.8349
2	8	31	2005	AMARE	Pigweed spp.	7	48.16455	7	149.8109
2	8	31	2006	AMARE	Pigweed spp.	7	62.29192	7	164.8424
2	8	31	2007	AMARE	Pigweed spp.	7	68.54207	7	171.3112
2	8	31	2008	AMARE	Pigweed spp.	7	71.23182	7	174.0715
2	8	31	2009	AMARE	Pigweed spp.	7	72.37954	7	175.2455
2	8	31	2010	AMARE	Pigweed spp.	7	72.86771	7	175.7443
2	8	31	2011	AMARE	Pigweed spp.	7	73.07509	7	175.956
2	8	31	2012	AMARE	Pigweed spp.	7	73.16313	7	176.0459
2	8	31	2013	AMARE	Pigweed spp.	7	73.20052	7	176.0444

Record: 1 of 10

FIGURE 7.28, example data from the WEEDPOP table.



WEEDCROP : Table

MULABEL	HYEAR	CROPTYPE	WEEDID	WEEDNAME	PRESSURE	DENSITY
2	2004	ICORN	AMARE	Pigweed spp.	6	20.69365
2	2005	ICORN	AMARE	Pigweed spp.	7	47.94094
2	2006	ICORN	AMARE	Pigweed spp.	7	62.00271
2	2007	ICORN	AMARE	Pigweed spp.	7	68.22384
2	2008	ICORN	AMARE	Pigweed spp.	7	70.90111
2	2009	ICORN	AMARE	Pigweed spp.	7	72.0435
2	2010	ICORN	AMARE	Pigweed spp.	7	72.5294
2	2011	ICORN	AMARE	Pigweed spp.	7	72.73582
2	2012	ICORN	AMARE	Pigweed spp.	7	72.82346
2	2013	ICORN	AMARE	Pigweed spp.	7	72.86066

Record: 1 of 10

FIGURE 7.29, example data from the WEEDCROP table.

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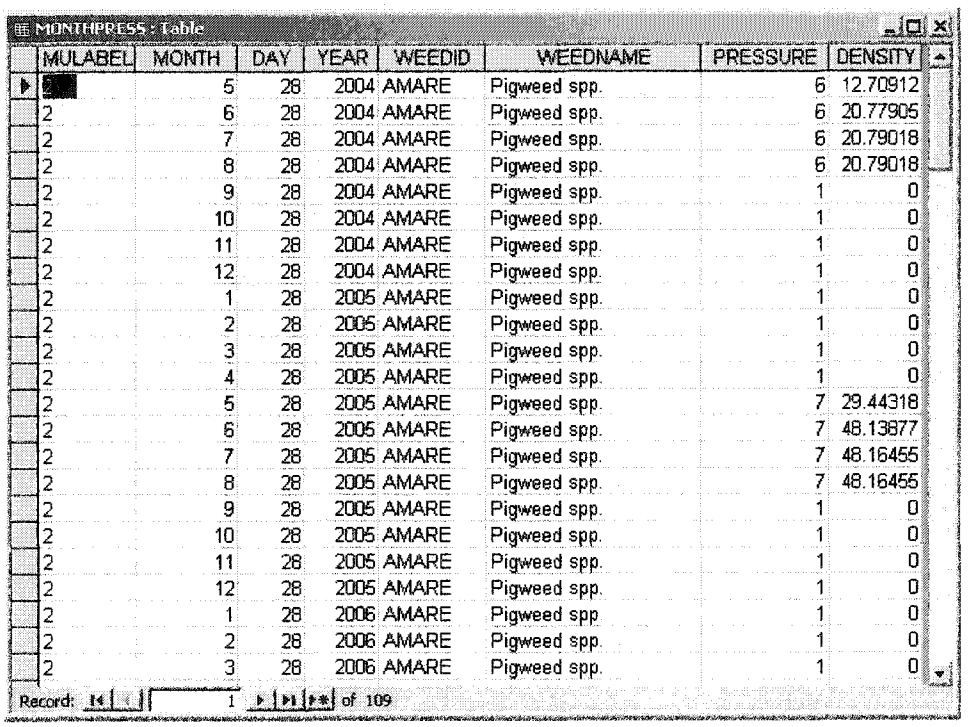

MONTHPRESS : Table

MULABEL	MONTH	DAY	YEAR	WEEDID	WEEDNAME	PRESSURE	DENSITY
2	5	28	2004	AMARE	Pigweed spp.	6	12.70912
2	6	28	2004	AMARE	Pigweed spp.	6	20.77905
2	7	28	2004	AMARE	Pigweed spp.	6	20.79018
2	8	28	2004	AMARE	Pigweed spp.	6	20.79018
2	9	28	2004	AMARE	Pigweed spp.	1	0
2	10	28	2004	AMARE	Pigweed spp.	1	0
2	11	28	2004	AMARE	Pigweed spp.	1	0
2	12	28	2004	AMARE	Pigweed spp.	1	0
2	1	28	2005	AMARE	Pigweed spp.	1	0
2	2	28	2005	AMARE	Pigweed spp.	1	0
2	3	28	2005	AMARE	Pigweed spp.	1	0
2	4	28	2005	AMARE	Pigweed spp.	1	0
2	5	28	2005	AMARE	Pigweed spp.	7	29.44318
2	6	28	2005	AMARE	Pigweed spp.	7	48.13877
2	7	28	2005	AMARE	Pigweed spp.	7	48.16455
2	8	28	2005	AMARE	Pigweed spp.	7	48.16455
2	9	28	2005	AMARE	Pigweed spp.	1	0
2	10	28	2005	AMARE	Pigweed spp.	1	0
2	11	28	2005	AMARE	Pigweed spp.	1	0
2	12	28	2005	AMARE	Pigweed spp.	1	0
2	1	28	2006	AMARE	Pigweed spp.	1	0
2	2	28	2006	AMARE	Pigweed spp.	1	0
2	3	28	2006	AMARE	Pigweed spp.	1	0

Record: 1 of 109

FIGURE 7.30, example data from the MONTHPRESS table.

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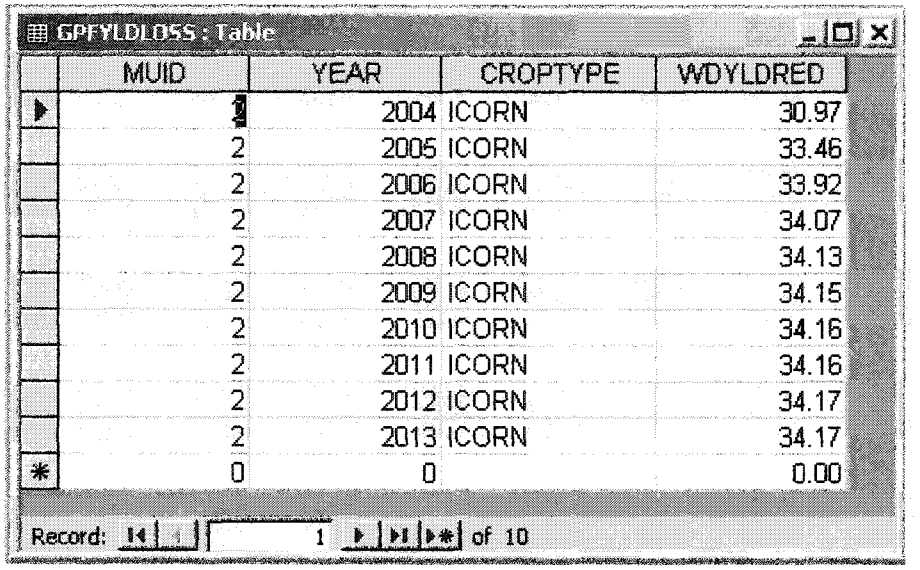

GPFYLDLOSS : Table

MUID	YEAR	CROPTYPE	WDYLDRED
1	2004	ICORN	30.97
2	2005	ICORN	33.46
2	2006	ICORN	33.92
2	2007	ICORN	34.07
2	2008	ICORN	34.13
2	2009	ICORN	34.15
2	2010	ICORN	34.16
2	2011	ICORN	34.16
2	2012	ICORN	34.17
2	2013	ICORN	34.17
0	0		0.00

Record: 1 of 10

FIGURE 7.31, example data from the GPFYLDLOSS table.

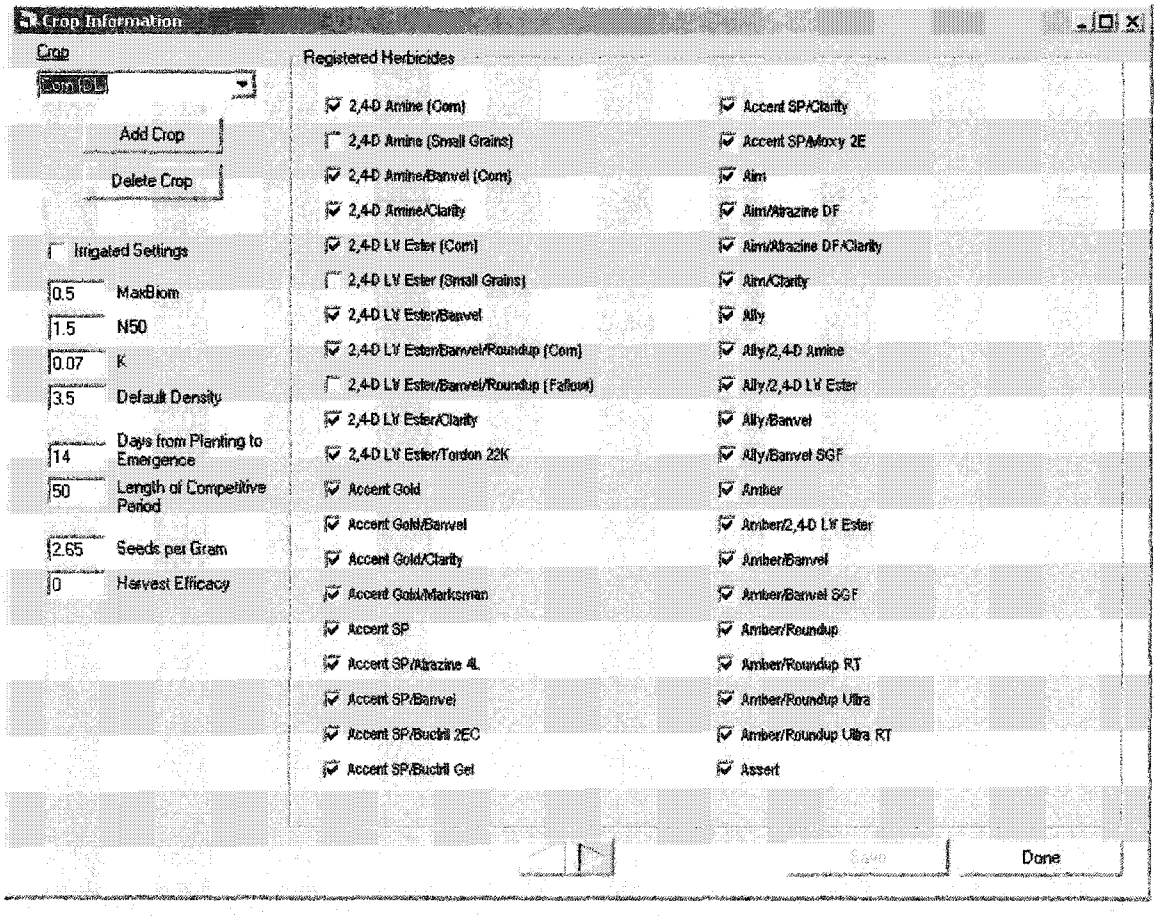

FIGURE 7.32, the Crop Information administrative form.

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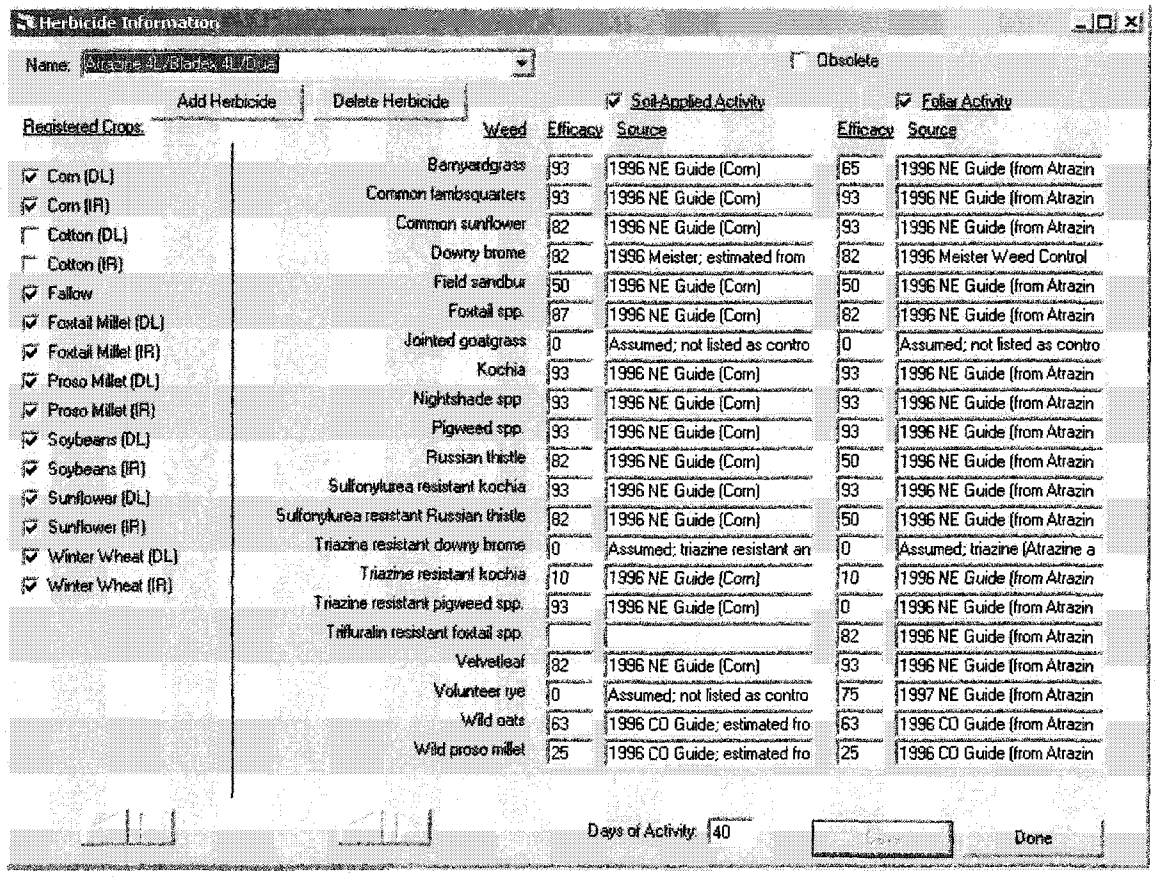

FIGURE 7.33, the Herbicide Information administrative form.

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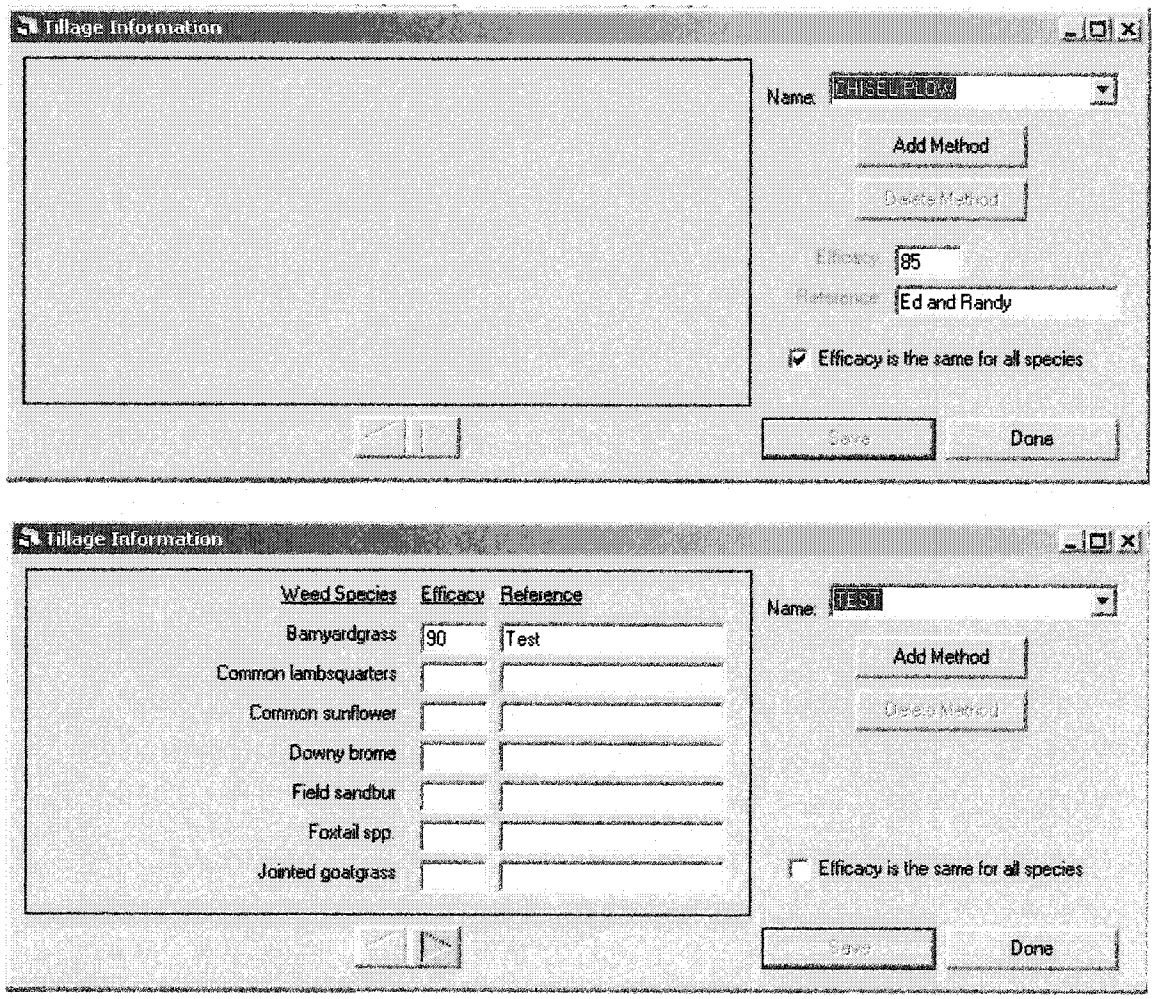

FIGURE 7.34, the Tillage Information administrative form, showing its controls with species-specific efficacy turned off and on, respectively.

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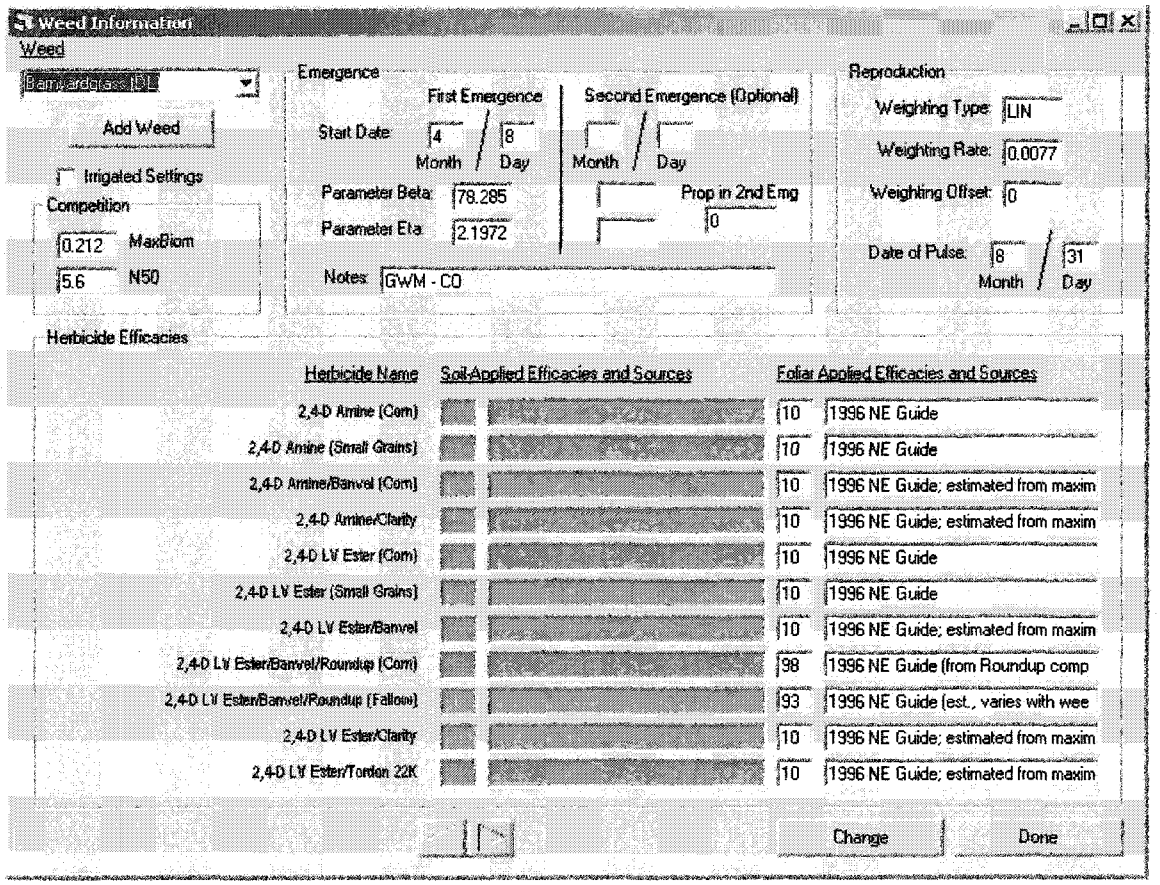

FIGURE 7.35, the Weed Information administrative form.

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Chapter 8.0
The WISDEM Model II: Validation and Experiments

"If you can look into the seeds of time,
And say which grain will grow and which will not,
Speak then to me."

William Shakespeare
Macbeth I.iii.

8.1 Abstract

WISDEM (Weed Interference and Simple Demographic Model) is a decision-aid model developed initially by Wiles et al. (1996) and recently augmented in response to some major theoretical work by Canner, Wiles, and McMaster (2002). This model has been significantly upgraded by the present author and is presented as an ecologically-based approach to the simulation of weed shifts as well as a realistic decision-aid management tool for glyphosate-tolerant cropping systems, specifically for selecting optimal weed management products and optimal application timings in glyphosate-tolerant corn (*Zea mays*). A successful validation is performed on data from a study at the ARDEC facility at Colorado State University, and successfully realistic management recommendations are made for this site.

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8.2 Introduction

WISDEM (Canner et al., 2003) is the latest generation of a model lineage exemplified most strongly by the GWM model (Wiles et al., 1996). Specifically in this latest generation aspects of relative time of emergence are modeled more explicitly in regards to plant competition and weed seed production. In addition, the model parameterization has been simplified by an assumption introduced by Canner, Wiles, and McMaster (2002) that model parameters involved in weed seed production are relatable, and, thus, obtainable, from parameters involved in crop yield loss.

WISDEM has recently undergone some additional algorithmic enhancements, where smooth weighting functions now govern the reduction of weed fecundity for late-emerging cohorts, and the competitive effect of weeds on the crop is now governed by average densities over a critical competitive period. Lastly, many weed emergence curves have been parameterized.

The objective of this study was to investigate this new model through an initial validation in Roundup Ready™ corn. In addition, with a successful validation some successful management recommendations and ecological insight are desired.

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8.3 Model Validation

Some validation simulations were performed in comparison with a Roundup Ready™ cropping study performed at the ARDEC facility at Colorado State University. This validation was compared with data from continuous corn, and the crop production scenario in WISDEM was represented by the seasonal events listed in TABLE 8.1. The runs in WISDEM simulated densities for the following weed species appearing together:

Velvetleaf	(*Abutilon theophrasti*)
Redroot pigweed	(*Amaranthus retroflexus*)
Common lambsquarters	(*Chenopodium album*)
Barnyardgrass	(*Echinochloa crus-galli*)
Common sunflower	(*Helianthus petiolaris*)
Kochia	(*Kochia scoparia*)
Nightshade spp.	(*Solanum spp.*)

Deducing initial potential densities, $N_{potential}$, for each species proved to be nontrivial, since in the field study no plots existed that showed densities under no control measures. Observations were taken of weed densities in early June, but such observations took place approximately six weeks after a pre-plant tillage event. Thus, in order to deduce total potential density, one had to hypothesize what proportion of total cohorts for the full season had emerged between the date of the tillage event and the date

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of observation. This proportion was calculated for each species as the difference in the Weibull distribution value between 17 April and 2 June for each weed species. The observed density was then divided by this proportion to achieve a theorized initial potential density. This process is documented for each species in TABLE 8.2.

This methodology was problematic for common lambsquarters, as the emergence distribution for this species was parameterized as being largely completed by 17 April, and, thus, the difference in this distribution represented a very small proportion that resulted in an unrealistically large initial density of 50,000 plants per square meter. (This was actually reduced for the model run to 10,000 plants per square meter.) This strongly indicates that for future runs the emergence distribution for common lambsquarters may need to be further adjusted to the conditions of Colorado.

FIGURES 8.1 through 8.14 show the validation results for each of the seven species, displayed in the order that they are listed above. For each species two graphs are shown, one displaying observed and predicted densities as a function of time over six growing seasons, and the other plots observed weed densities directly against predicted densities. Note that in the plots over time the model results appear as a sequence of orange lines, one for each season. These lines connect points of nonzero weed densities output at the end of each month. Observed densities appear as yellow box-and-whisker plots, with the whiskers showing one standard deviation. The reader should also make note of the fact that density axes are logarithmic on all plots. The results were generally positive for redroot pigweed, barnyardgrass, and kochia. The results for common

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lambsquarters generally confirmed that the emergence curve for this species was parameterized as occurring too early in the season. The results for velvetleaf and sunflower generally indicated an underestimation of density which may be due to a similar issue with the emergence curves. Lastly, the results for nightshade generally showed observed dynamics that had no observable long-term trend, and were, thus, most likely representative of season-specific environmental dynamics of which WISDEM has no algorithmic knowledge. Thus, results were poor for this species.

It should also be pointed out that species other than those listed in this analysis were also observed in the field study, but generally to a lesser degree. This model validation study captured the most common species, and, thus, it is hoped, the most important dynamics.

8.4 Some Experiments

Inasmuch as the results depicted in the preceding validation imply an adequate depiction of significant core processes involved in the weed population dynamics of the featured cropping systems, WISDEM can be utilized to gain decision-making insight into such systems as well as demonstrate how such insight can be gained in other systems in the future. Three such simulated "experiments" are featured, each of which take place in continuous Roundup Ready™ corn planted on 1 May of each year and harvested on 1 November.

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8.4.1 When Does a Reduction in Glyphosate Efficacy Become a Problem?

For this experiment repeated runs were made in WISDEM with the efficacy of Roundup Ultra™ slowly reduced in an effort to ascertain at what point weed populations are no longer effectively controlled (i.e., populations are no longer decreasing from year to year). This was done individually for two species, common lambsquaters (*Chenopodium album*) and barnyardgrass (*Echinochloa crus-galli*).

For kochia two applications of Roundup Ultra™ were applied each year on 30 April and 21 May. The theorized common lambsquarters distribution of emergence timings is shown in FIGURE 8.15. FIGURE 8.16 shows late-season densities of common lambsquarters for ten simulated seasons under different efficacies of Roundup Ultra™. Note that control efficacies of 75 to 80 percent represent the cutoff point at which long-term effective control is no longer occurring. This percent efficacy would approximately correspond to a control rating of 6 or 7 in the *Guide for Weed Management in Nebraska* (Comfort et al., 2003).

FIGURE 8.17 shows that the theorized distribution of emergence timings for barnyardgrass occurs much later in the season than common lambsquarters. For this reason an additional application of Roundup Ultra™ was added on 10 June each year, although the figure clearly shows that even with this additional application there is a strong late-season cohort that is not controlled. Late-season simulated densities of

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barnyardgrass are displayed in FIGURE 8.18, and in particular it becomes visible that a different long-term dynamic occurs with a late-emerging weed species. Note that for this weed species two runs were initiated for each herbicide efficacy, and that these two runs began at different initial population levels. Presumably due to the late-emerging cohorts, exponential population reductions are never observed even for the highest efficacies. Rather, the populations appear to approach a stable equilibrium that is independent of the initial population level, but highly dependent upon the efficacy of the herbicide. This has important implications with respect to the management of late-emerging weeds in that if this equilibrium population level is high enough to be of significant influence to the crop yield or perhaps even compromising the economic feasibility of the cropping system, then long-term weed management plans may need to involve late-season control techniques or the rotation with another crop that allows for herbicide applications later in the season.

8.4.2 Decision Making – Optimal Products

The latter two experiments involved numerous WISDEM simulations in an effort to optimize decision-making processes associated with the crop production scenario illustrated in TABLE 8.1. Specifically for this experiment the pre-plant tillage event was removed, and WISDEM was utilized to simulate multiple burndown herbicide applications for a suitable replacement. Such a replacement would represent the conversion of this scenario to a completely "no-till" scenario.

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The herbicide applications that served as candidates for the pre-plant burndown event are listed in TABLE 8.3. WISDEM was used to simulate crop yield losses over a period of six years with each of these herbicide applications occurring on 17 April.

For a comparative evaluation an economic rubric was necessary. A value denoted here as "adjusted gross profits" (AGP) was defined as follows:

$$AGP = \sum_{k=1}^{6} \left(P_{corn} Y - C_{herb} \right) w_k$$

where P_{corn} and C_{herb} are the price of corn (per bushel) and the per-acre cost of the herbicide, respectively. Per-acre yield is denoted as Y and is calculated thus:

$$Y = Y_{wf} \left(1 - y_L \right)$$

where Y_{wf} and y_L are the weed-free yield and the proportional yield loss, respectively. Lastly, w_k is a weighting that is applied to each year:

$$w_k = \frac{i}{1 - (1+i)^{-k}} (1+i)^{-k}$$

It was first observed in King et al. (1986). It essentially applies greater weighting of profits to earlier years, since these years have a longer time to compound interest. In the above equation i represents an interest rate compounded annually.

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With the above in mind, the mathematical phrase ($P_{corn}Y - C_{herb}$) represents a kind of net profit which, of course, excludes other agronomic costs that are assumed to not vary with the choice of herbicide. AGP, thus, represents a total of these adjusted (w_k) net profits over a period of six years.

For the analysis the price of corn, P_{corn}, was set to $2.20 per bushel, the weed-free yield Y_{wf} was set to 176 bushels per acre, and the annual interest rate, i, was set to

The results are displayed in TABLE 8.3, where the two highest ranking choices, shown in boldface, are Atrazine 4L and a tank mixture of Roundup Ultra™ and 2,4–D Amine. This has been confirmed as a realistic result (Westra, personal communication), and it confirms the potential of WISDEM to be used as a decision-making bioeconomic tool for the optimal choosing of weed control products and techniques.

8.4.3 Decision Making – Optimal Application Timings

Returning again to the crop production scenario listed in TABLE 8.1 (with the pre-plant tillage event retained), we next focused on the optimal timings of the applications of Roundup Ultra™. WISDEM was run multiple times with different herbicide application timings, and adjusted gross profits (AGP) were calculated in the same way as in Experiment 2.

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This experiment began with restricting the scenario to a single herbicide application, the results of which are displayed in FIGURE 8.19, showing adjusted gross profits plotted against the date of the herbicide application. Here a date is observed in which AGP is maximized. The date is 29 May.

We then allowed for two applications of Roundup Ultra™. The process of finding a maximum AGP involved an iterative process illustrated in TABLE 8.4, where one application date was held constant while another was varied until a maximum was reached. The previously constant application date was then varied as the previously varied application date was now held constant, again until a maximum was reached, and so on. The process ended when variation of either application date resulted in a reduction of AGP. The two resulting dates were 15 May and 5 June. Again, these dates have been confirmed as realistic (Nissen, personal communication).

It is also interesting to note that for this experiment variation of the economic parameters resulted in no shift in these optimal dates. The above maxima represent purely ecological phenomena, not economic phenomena. Thus, not only is the potential of WISDEM for serving as a helpful decision-aid demonstrated here, but it is also indicated that such decision-aid results will be only dependent on agronomic conditions and not dependent on marketplace conditions.

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8.5 Conclusions and Next Steps

The WISDEM model has undergone modifications, both algorithmic and programmatic. Its algorithmic modifications have focused on the advent of reductions in weed fecundity with changes in emergence timing as well as allowing the effects of weeds on a crop to be averaged over a critical period of crop competitive vulnerability. Its programmatic modifications have involved a reorganization of the model code, an upgrade to its database protocols, and the beginning of a redesign of its interface.

Initial simulations using WISDEM have yielded results that are reasonably consistent with results from a nearby field study involving Roundup Ready™ crops. The results imply that present ecological understanding of weed-crop interference and relative emergence timing may be able to explain much of what occurs in agronomic scenarios. In addition, sensitivity analyses suggest that significant improvement in model performance may be possible through a more explicit and season-dependent depiction of weed emergence patterns.

Lastly, simulated experiments using WISDEM have indicated a 75 to 80% threshold for adequate long-term control of common lambsquarters by glyphosate, although for other more late-emerging weed species this threshold may be quite different and in fact may be nonexistent. WISDEM has also demonstrated some ability at predicting optimal products and application timings for decision-making processes.

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In the short-term, some final steps are warranted in this stage of the implementation. Appropriate demographic parameters for cotton need to be calculated and entered, and herbicide efficacies for cotton and soybeans need to be entered. The administrative forms need to be fully completed and updated to reflect additional newly created demographic parameters. In addition, some additional validations involving crops other than corn are also warranted. Lastly, there is a noteworthy technical database issue that will need to be resolved prior to the completion of this project.

At the completion of this project, two additional steps are warranted. The first will be the design and implementation of a full user interface for the WISDEM model. To some extent the design of this interface has already taken place (Dharmasri, personal communication) and may involve a web-based implementation. Secondly, the expansion of applicability of this model to different geographic regions may require region-specific parameterizations and environmentally-driven emergence curves.

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Continuous Corn Crop Production Scenario	
April 17	**Pre-Plant Tillage**
May 1	**Planting**
June 10	**Application of Roundup Ultra™**
July 10	**Application of Roundup Ultra™**
November 1	**Harvest**

TABLE 8.1, the modeled crop production scenario for the validation runs.

Weed	Observed Density	W(4/17)	W(6/2)	Weibull Scale Factor	Npotential (plants/ha)	Npotential (plants/m^2)
ABUTH	18563.52	0	0.451531	0.451531264	41112.36913	4.111236913
AMARE	2755839	0	0.909509	0.909508558	3030030.938	303.0030938
CHEAL	2031862	0.996004	1	0.003996	508473911.4	50847.39114
ECHCG	1795599	0.00859	0.357382	0.348792231	5148046.884	514.8046884
HELAN	37127.04	0.996004	1	0.003996	9291051.051	929.1051051
KCHSC	43877.41	0.243479	0.985378	0.741898743	59142.04659	5.914204659
SOLXX	3375.19	0	0.514463	0.514463105	6560.60652	0.656060652

TABLE 8.2, the sequence of steps for deducing assumed initial potential densities for the seven weeds in the validation exercise.

Run	Description	AGP	Rank
A	2,4-D Amine	$247.19	5
B	**Atrazine 4L**	**$416.02**	**1**
C	Gramaxone Max	$271.69	4
D	Roundup Ultra	$354.59	3
E	**Roundup Ultra / 2,4-D Amine**	**$365.69**	**2**

TABLE 8.3, five options evaulated bioeconomically by WISDEM for the replacement of the pre-plant tillage event.

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App 1	App 2	AGP
29-May	31-May	$744.77
28-May	31-May	$749.35
27-May	31-May	$753.65
26-May	31-May	$757.74
25-May	31-May	$761.57
24-May	31-May	$765.19
23-May	31-May	$768.58
22-May	31-May	$771.72
21-May	31-May	$774.61
20-May	31-May	$777.27
19-May	31-May	$779.73
18-May	31-May	$781.91

App 1	App 2	AGP
17-May	31-May	$783.87
16-May	31-May	$785.65
15-May	31-May	$787.27
14-May	31-May	$784.25
15-May	1-Jun	$788.48
15-May	2-Jun	$793.66
15-May	3-Jun	$795.59
15-May	4-Jun	$796.74
15-May	5-Jun	$797.17
15-May	6-Jun	$796.73
14-May	5-Jun	$792.78
16-May	5-Jun	$796.93

TABLE 8.4, options for the dates of two applications of Roundup Ultra™ along with adjusted gross profits. Note the iterative nature of the comparison process and the optimal choice shown in white lettering.

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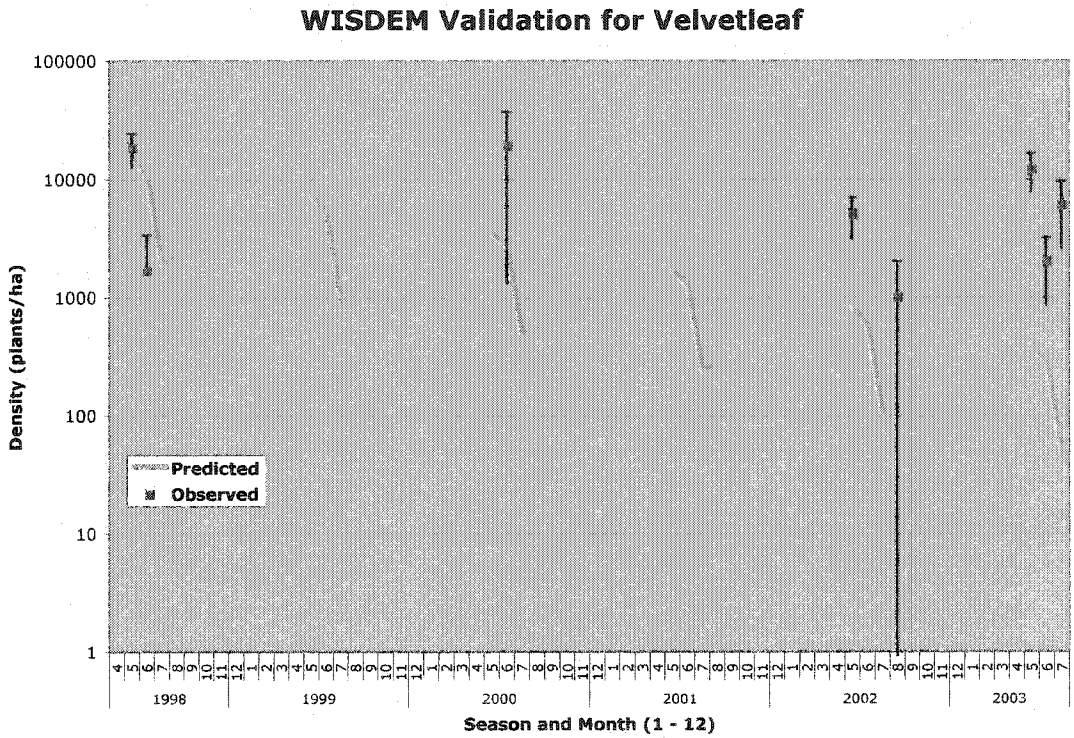

FIGURE 8.1, observed and predicted densities for velvetleaf (*Abutilon theophrasti*).

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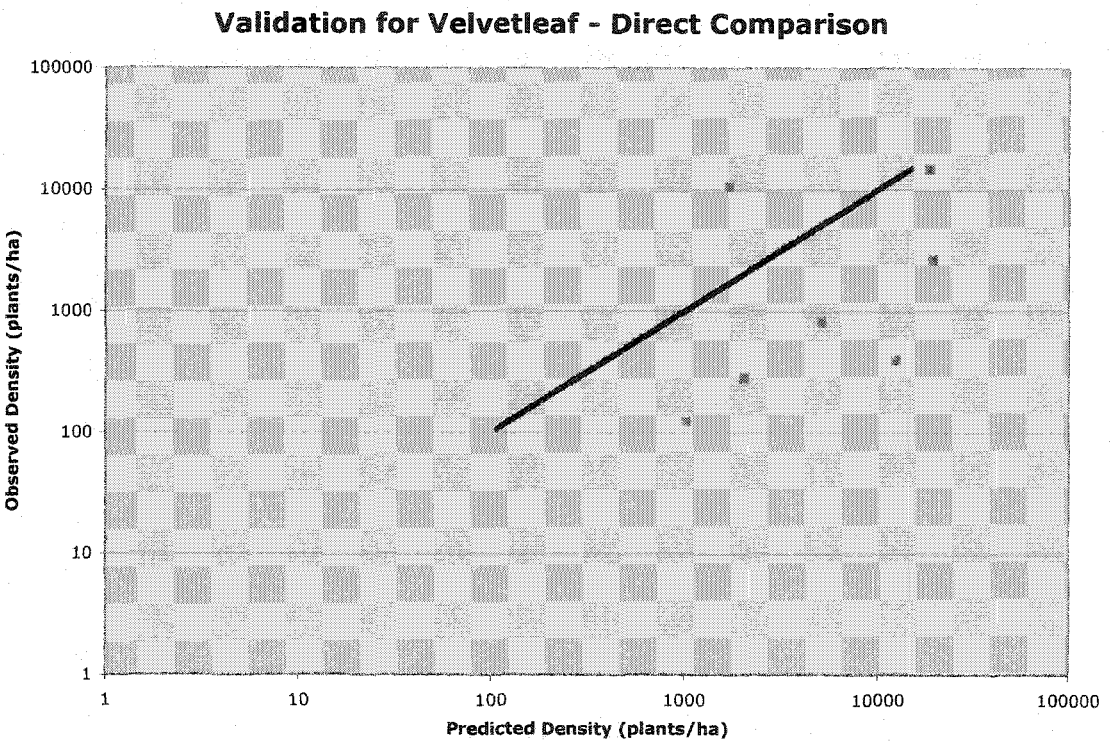

FIGURE 8.2, direct comparisons of observed and predicted densities of velvetleaf (*Abutilon theophrasti*).

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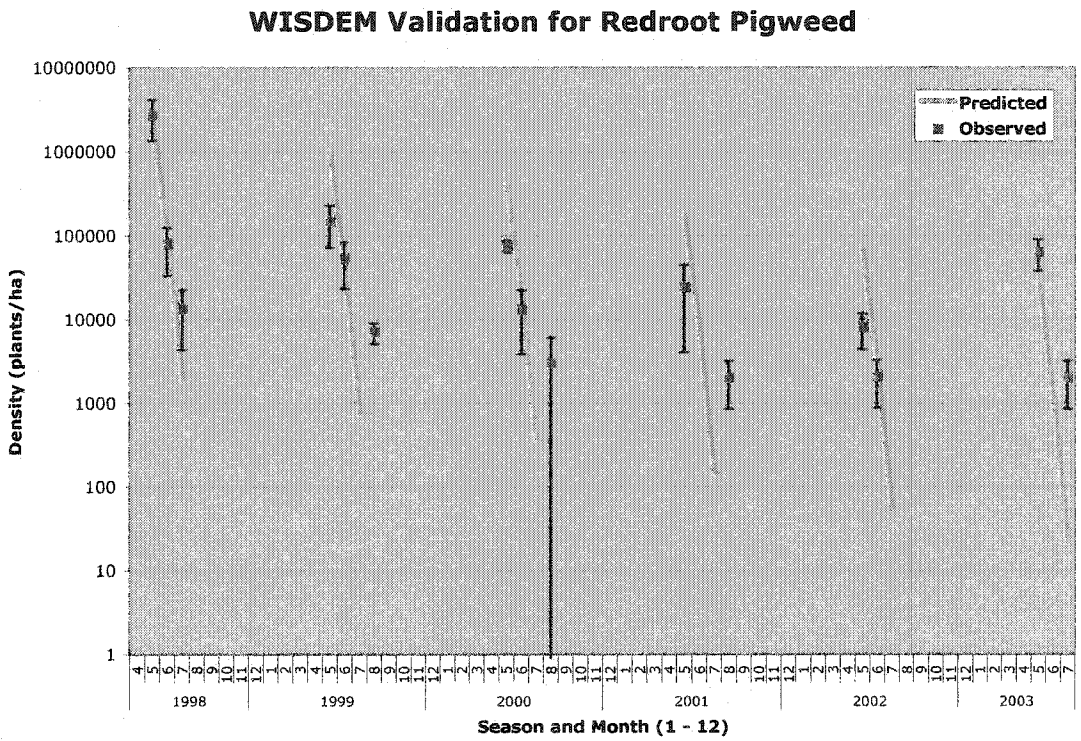

FIGURE 8.3, observed and predicted densities for redroot pigweed (*Amaranthus retroflexus*).

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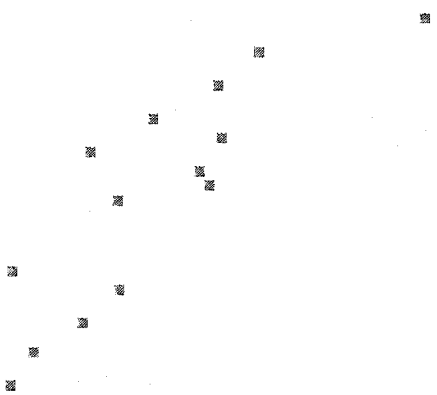

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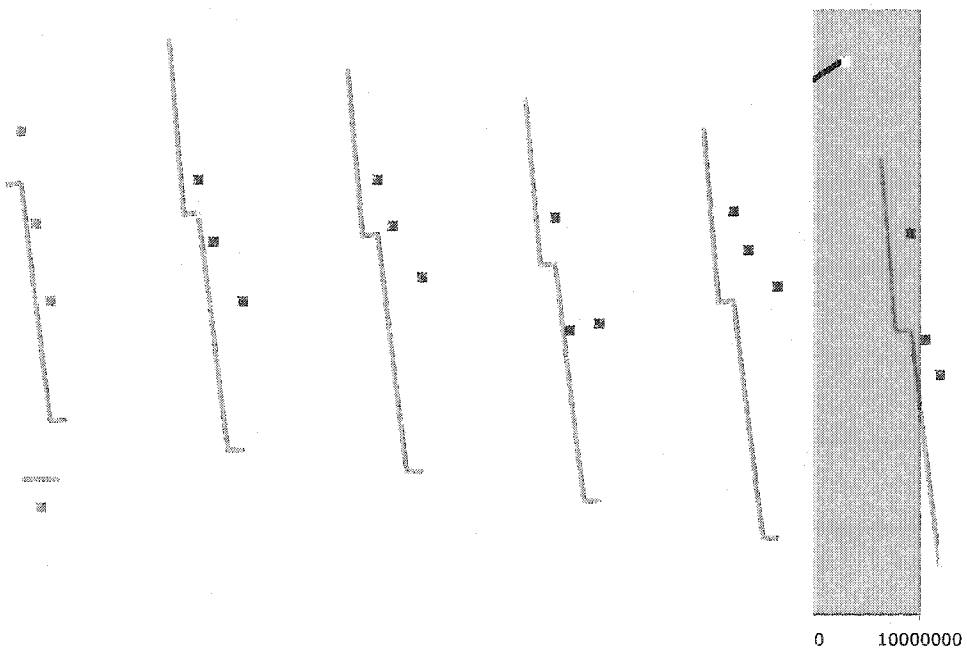

oot pigweed

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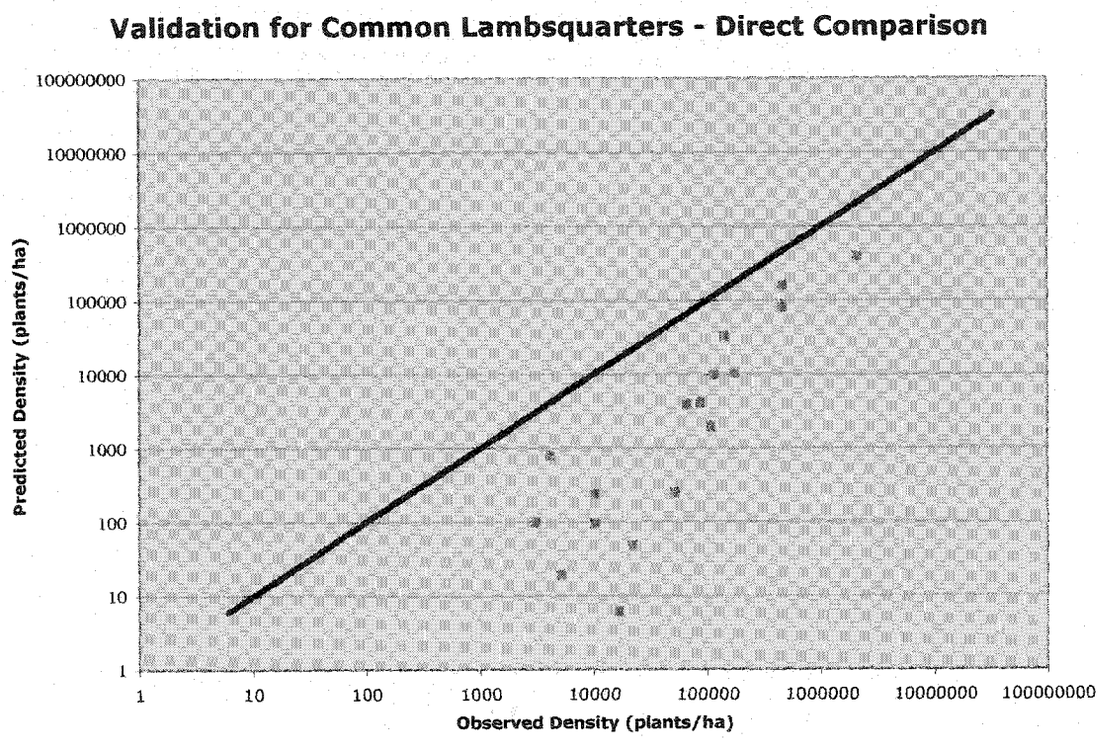

FIGURE 8.6, direct comparisons of observed and predicted densities of common lambsquarters (*Chenopodium album*).

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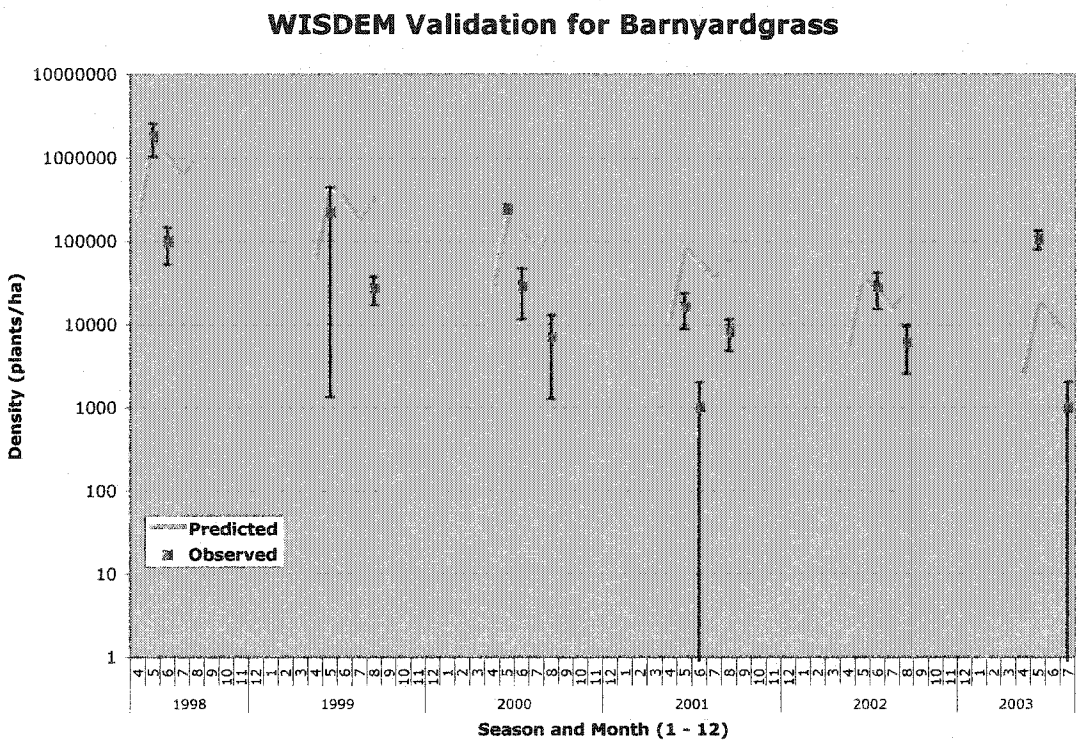

FIGURE 8.7, observed and predicted densities for barnyardgrass (*Echinochloa crus-galli*).

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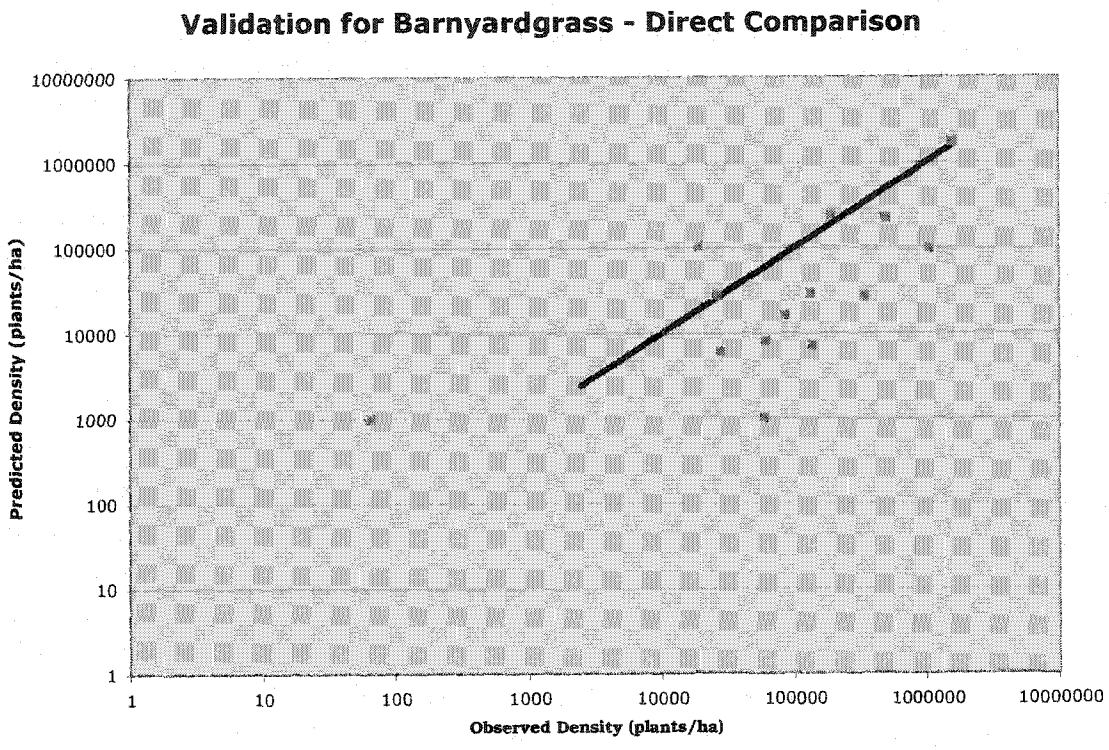

FIGURE 8.8, direct comparisons of observed and predicted densities of barnyardgrass (*Echinochloa crus-galli*).

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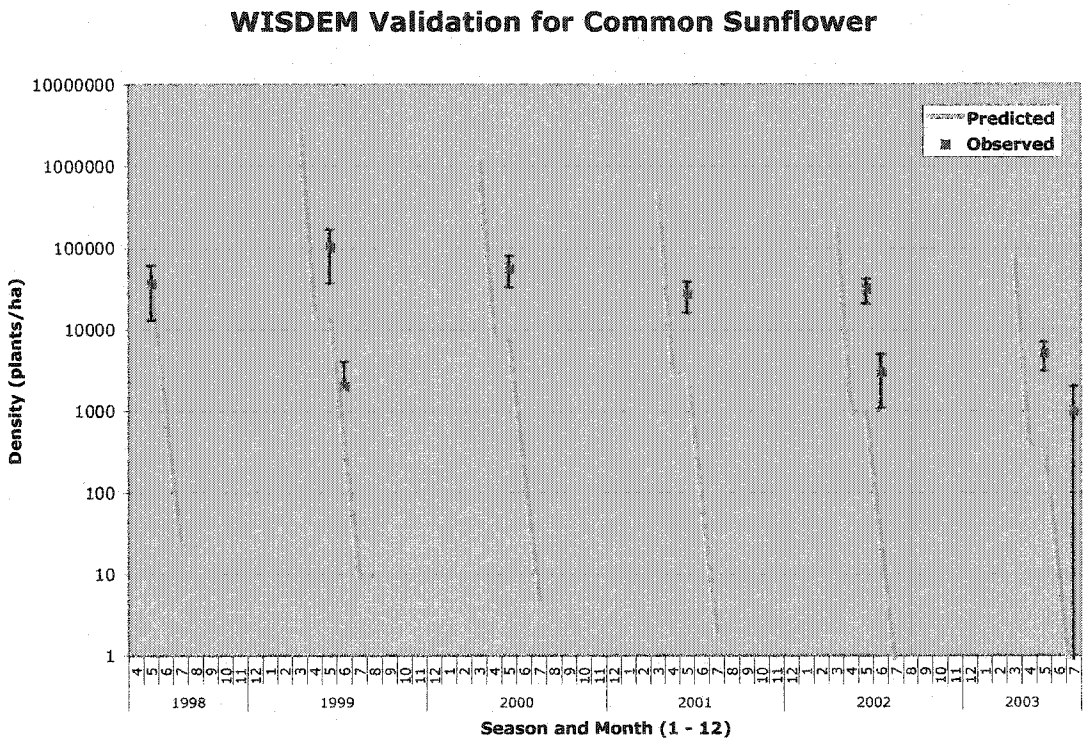

FIGURE 8.9, observed and predicted densities for common sunflower (*Helianthus petiolaris*).

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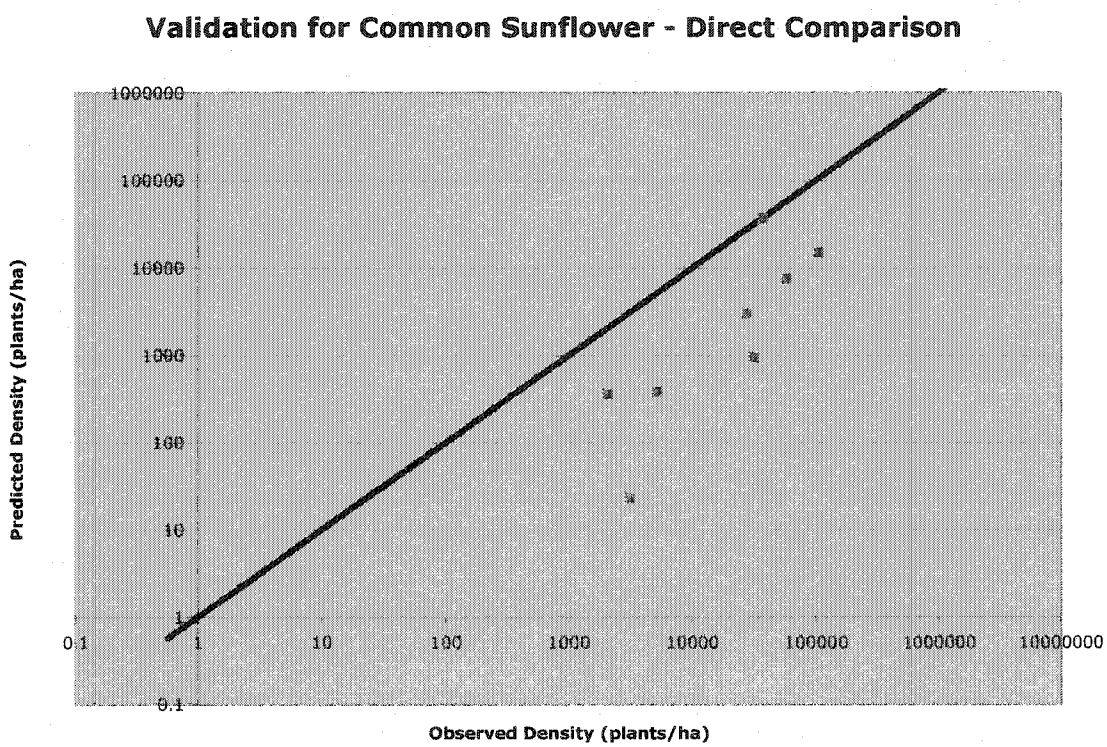

FIGURE 8.10, direct comparisons of observed and predicted densities of common sunflower (*Helianthus petiolaris*).

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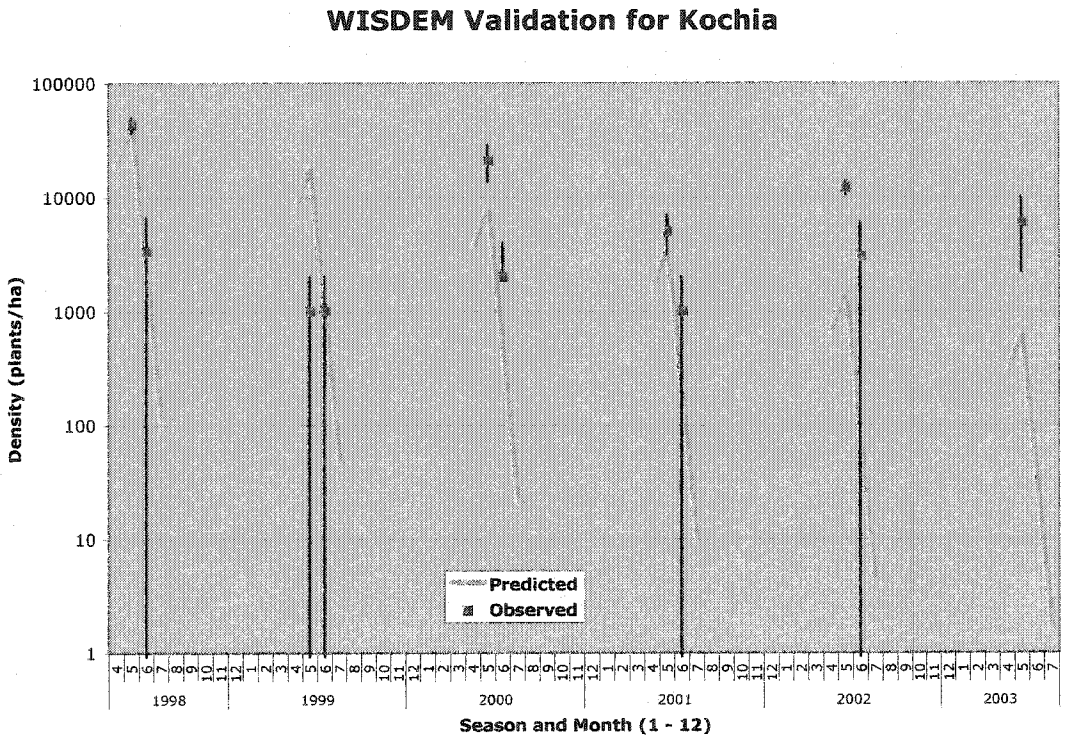

FIGURE 8.11, observed and predicted densities for kochia (*Kochia scoparia*).

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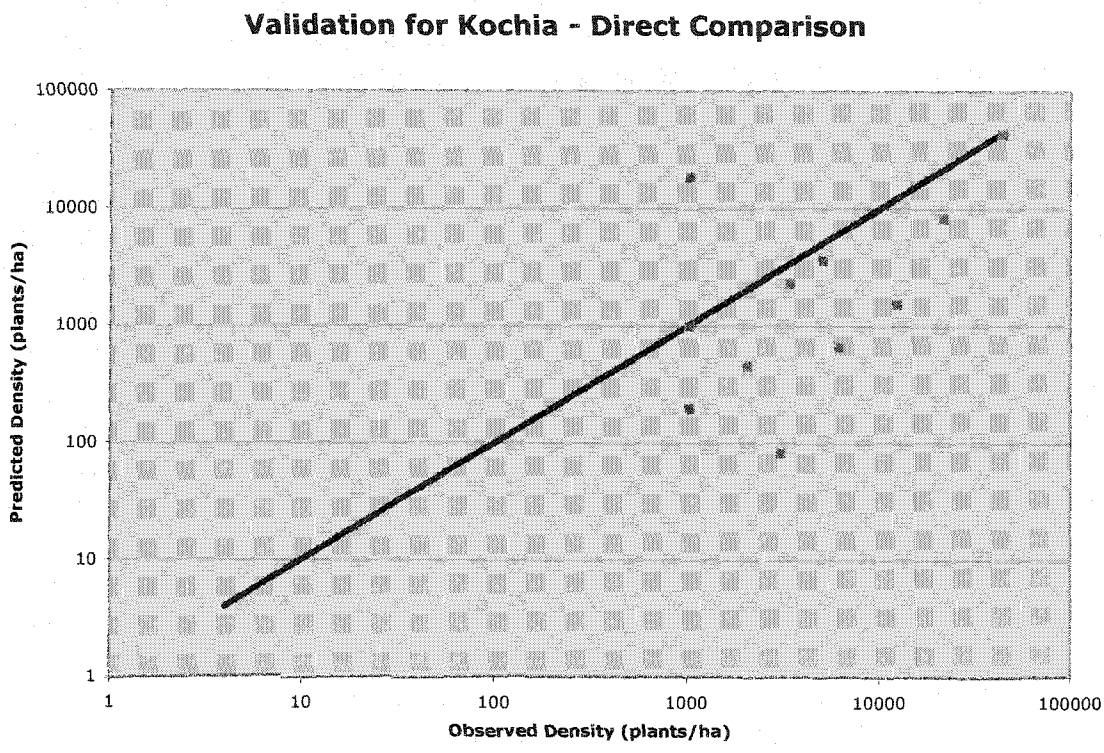

FIGURE 8.12, direct comparisons of observed and predicted densities of kochia (*Kochia scoparia*).

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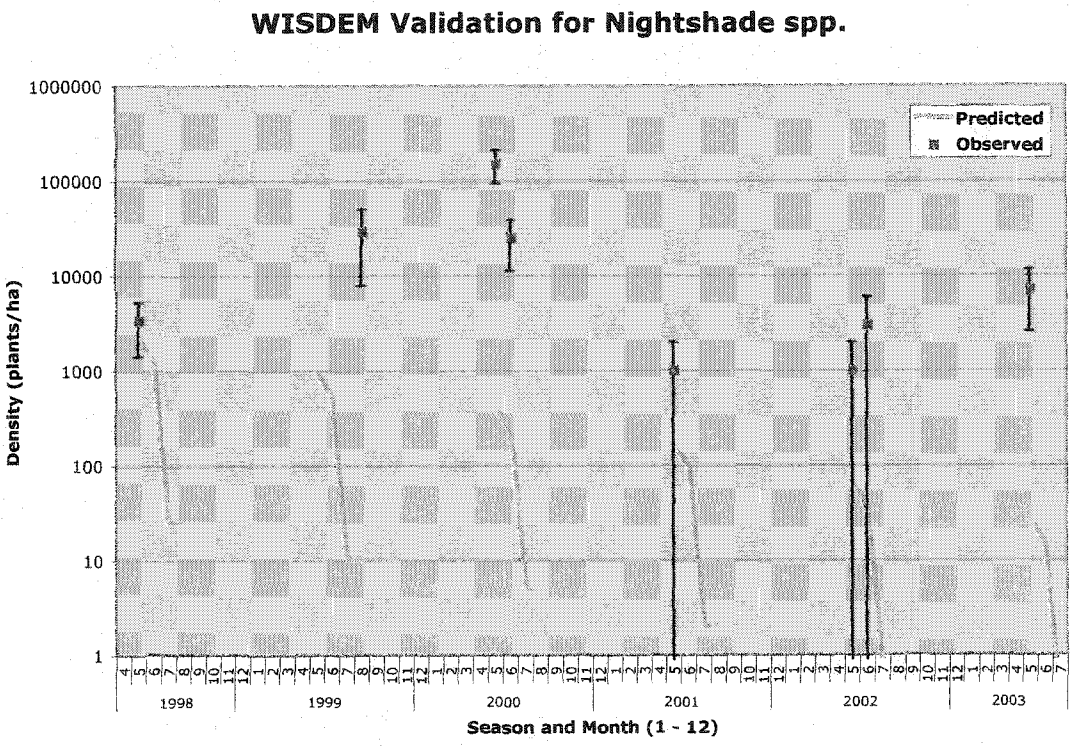

FIGURE 8.13, observed and predicted densities for nightshade spp. (*Solanum spp.*).

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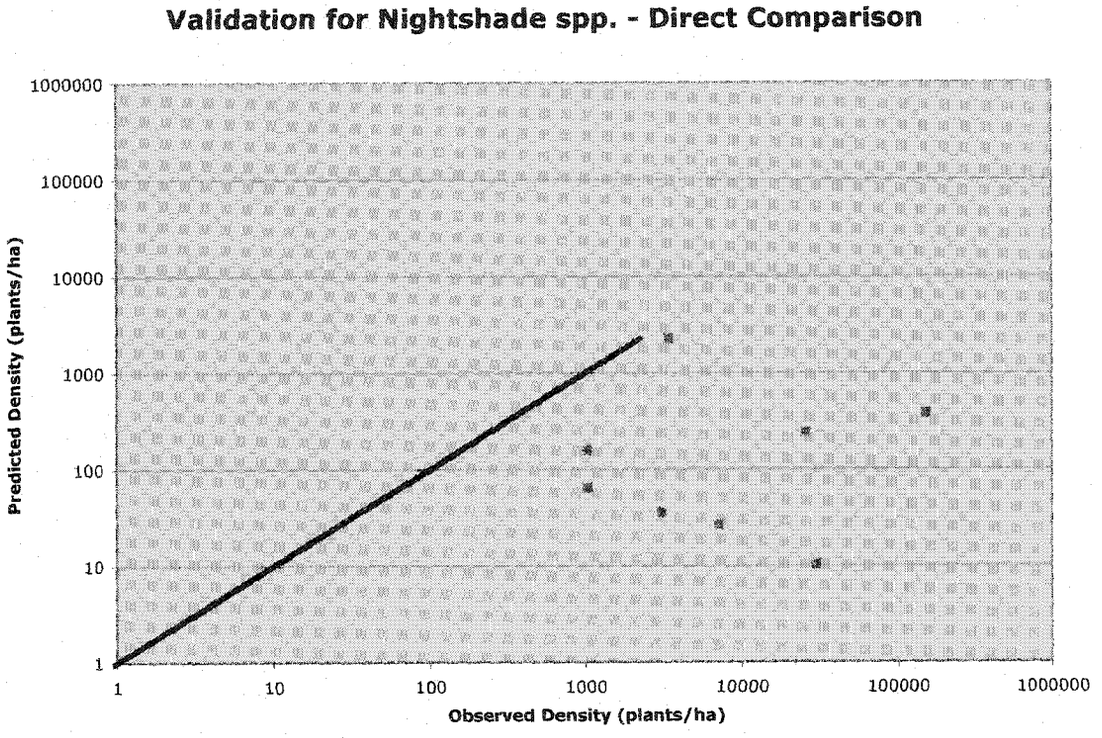

FIGURE 8.14, direct comparisons of observed and predicted densities of nightshade spp. (*Solanum spp.*).

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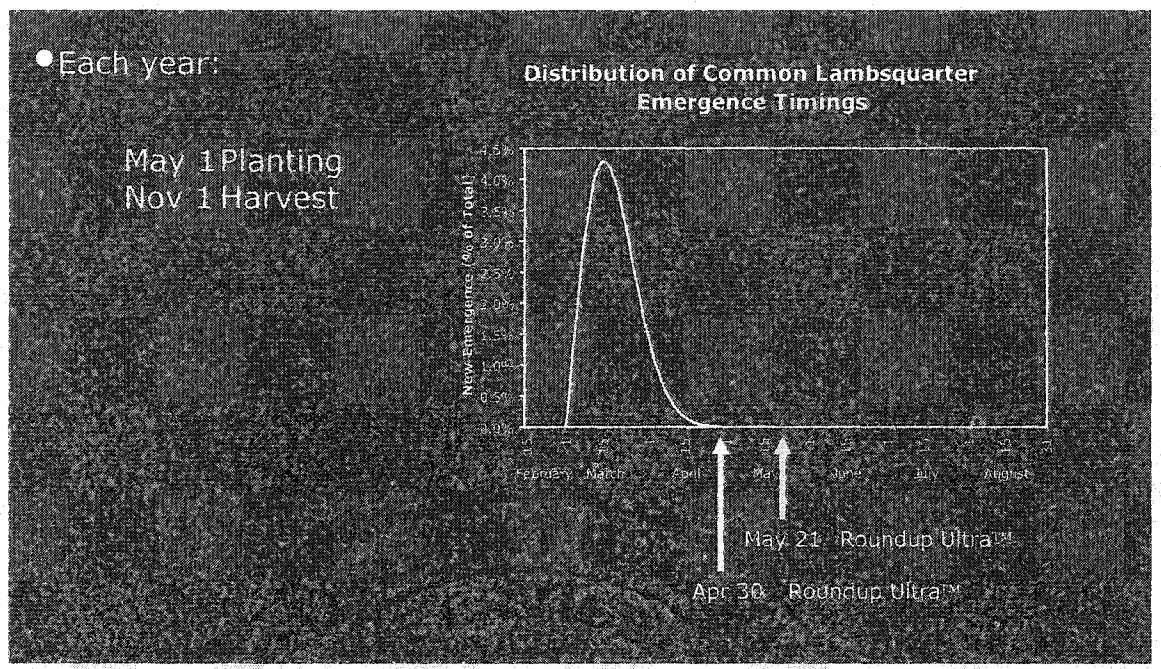

FIGURE 8.15, the theorized emergence distribution for common lambsquarters (*Chenopodium album*).

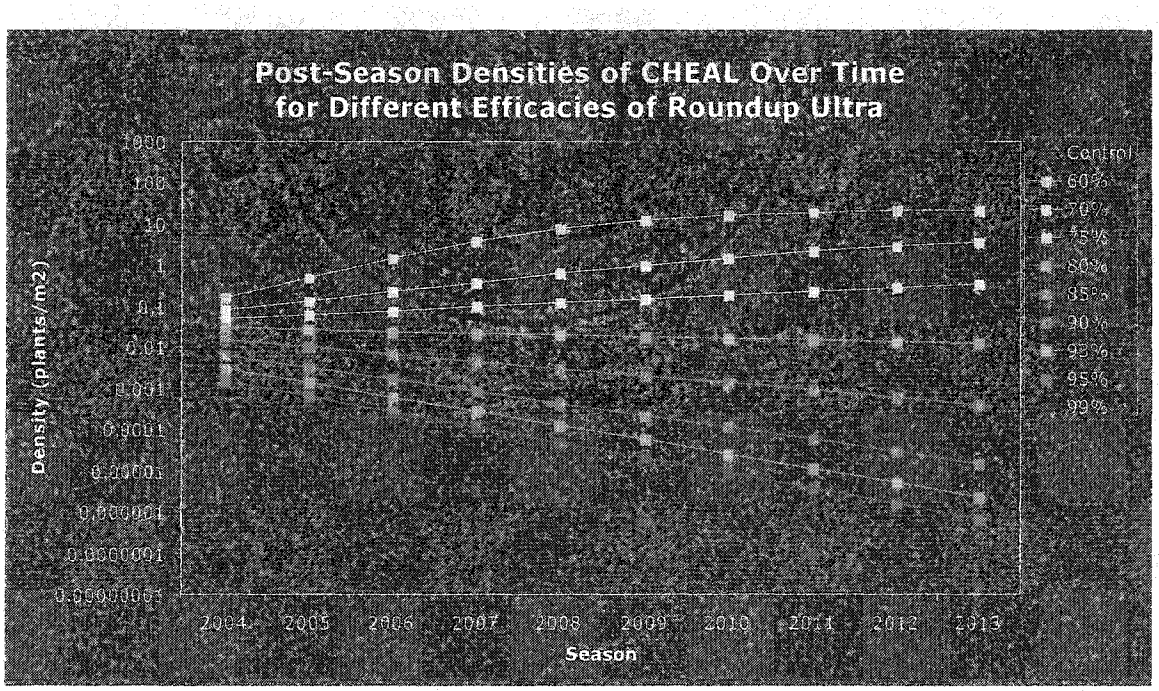

FIGURE 8.16, late-season densities of common lambsquarters (*Chenopodium album*) over ten simulated years in continuous corn. Two applications of Roundup Ultra™ are applied each year with varying efficacies.

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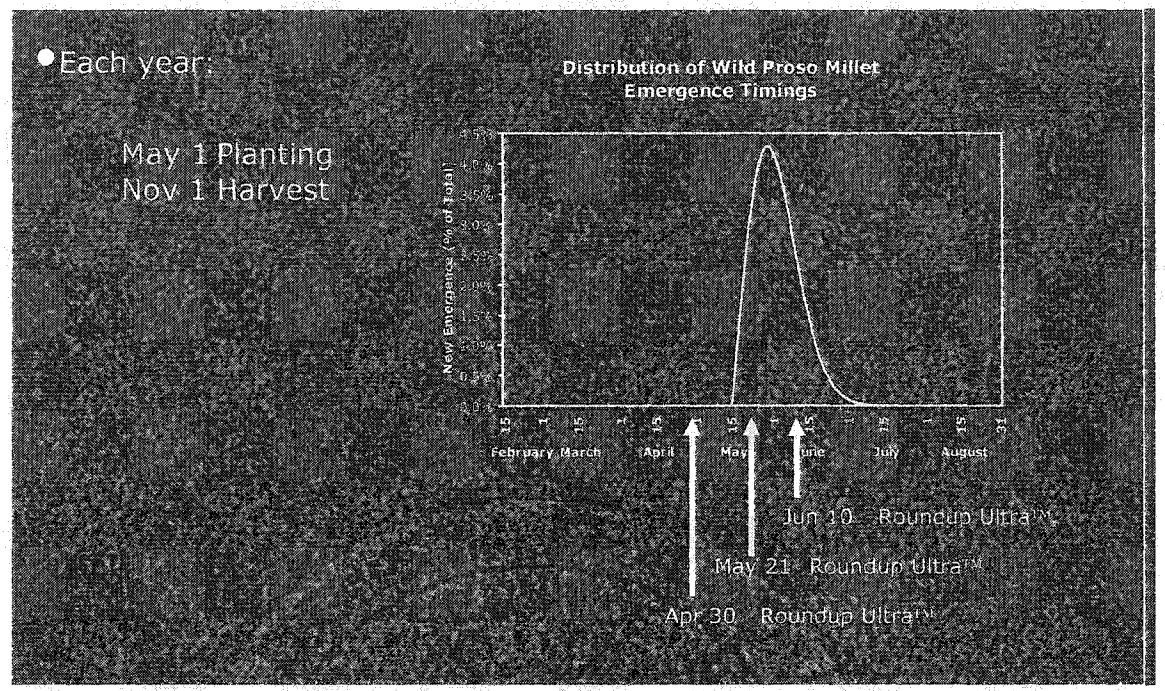

FIGURE 8.17, the theorized emergence distribution for wild proso millet (*Panicum milaceum*).

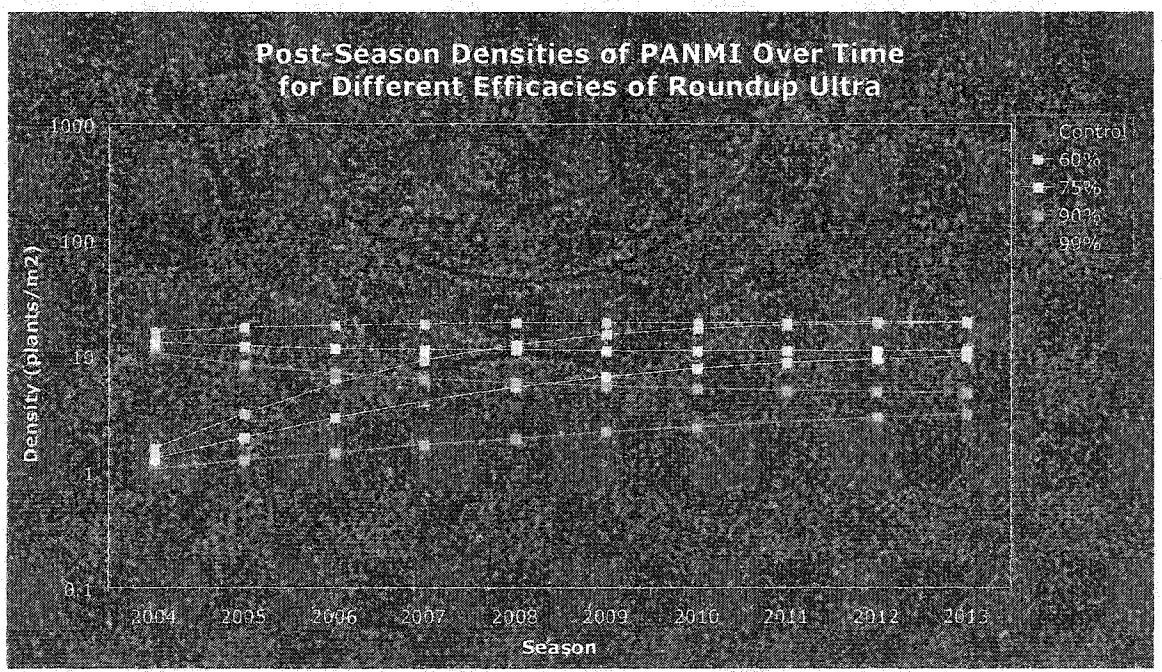

FIGURE 8.18, late-season densities of wild proso millet (*Panicum milaceum*) over ten simulated years in continuous corn. Two applications of Roundup Ultra™ are applied each year with varying efficacies.

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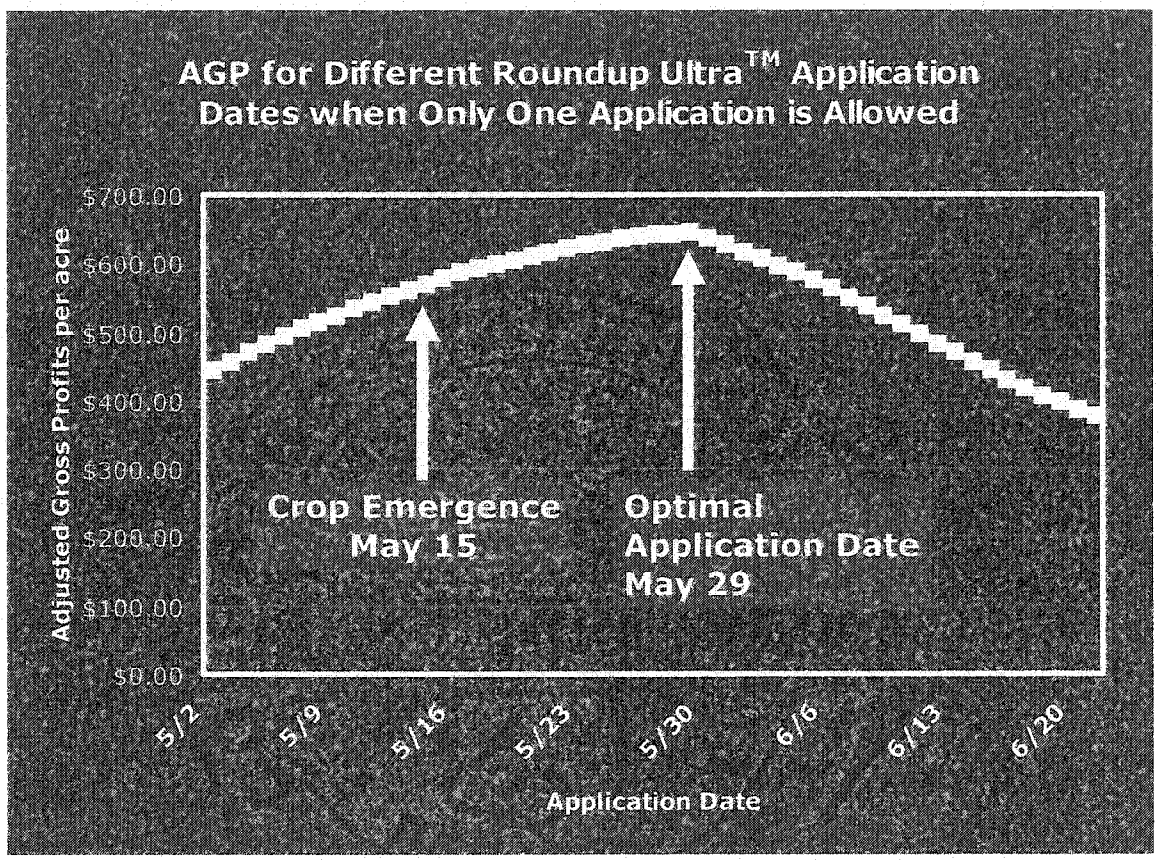

FIGURE 8.19, per acre adjusted gross profits for different dates of a single application of Roundup Ultra™ in continuous corn.

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Appendix A
Analytical Determinations of Economic Optimum Thresholds

In the context of a single year the determination of an economic optimum threshold (EOT) can be solved analytically. The presentation of such an analytical solution process in full detail is the purpose of this appendix.

The economic return of an herbicide application is defined as follows:

$$P_{return} = P_{herb} - P_{noherb}$$

Simply put, it is the difference in the total profits between spraying and not spraying. The total profits when not spraying have been summarized thus (e.g., Bauer and Mortensen, 1992):

$$P_{noherb} = C_c Y_{wf}\left(1 - y_{L,n}\right) - C_f$$

where C_c represents the price of the crop, Y_{wf} is the weed-free yield, and $y_{L,n}$ is the proportional yield loss from the presence of weeds. In effect the first term is the total gross profit of the sale of the crop, and the second term C_f is simply all of the agronomic operational costs not directly related to weed control (purchased materials, fuel,

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equipment maintenance and depreciation, rental costs, labor, taxes, etc.) With this in mind, the total profits when spraying does take place are as follows:

$$P_{herb} = C_c Y_{wf}\left(1 - y_{L,h}\right) - C_f - C_h - C_a$$

where a smaller proportional yield loss $y_{L,h}$ is used, and two new costs are added for the herbicide purchase and application (C_h and C_a, respectively).

The net return is derived from the difference in these two quantities:

$$\begin{aligned} P_{return} &= \left[C_c Y_{wf}\left(1 - y_{L,h}\right) - C_f - C_h - C_a\right] - \left[C_c Y_{wf}\left(1 - y_{L,n}\right) - C_f\right] \\ &= C_c Y_{wf}\left(y_{L,n} - y_{L,h}\right) - C_h - C_a \end{aligned}$$

(This is presented in a different form than that which is in Bauer and Mortensen, but the concept is the same.) As a reminder, here C_c, C_h, and C_a represent the market values (costs) of the soybean crop, herbicide purchase, and herbicide application, respectively, and Y_{wf}, $y_{L,h}$, and $y_{L,n}$ represent respectively the weed-free yield and the proportional yield losses with and without the herbicide application. The first term shows the financial gain of the herbicide, and the last two terms list its costs. With small weed densities the difference in yield losses $y_{L,n} - y_{L,h}$ with and without the herbicide is minimal, and so the first term is small, thus making the latter two terms most significant, showing the herbicide application to not be cost-effective. At sufficiently high weed densities, however, the above difference in projected yield losses is large, and when multiplied by

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the weed-free yield Y_{wf} and then by the price of the crop C_c, creates a gain large enough to offset the cost of herbicide purchase and application. The economic optimum threshold (EOT) is the break-even point between these two regimes, defined as the point where $P_{return} = 0$:

$$P_{return} = C_c Y_{wf} \left(y_{L,n} - y_{L,h} \right) - C_h - C_a \geq 0$$

or, equivalently through algebra:

$$y_{L,n} - y_{L,h} \geq \frac{C_h + C_a}{C_c Y_{wf}}$$

or,

$$y_{L,n} - y_{L,h} \geq \Psi \qquad [A.1]$$

where

$$\Psi = \frac{C_h + C_a}{C_c Y_{wf}}$$

gives an indication of how expensive the herbicide application is, given relative to the maximum (weed-free) gross profits of the crop. Thus, a value of $\Psi = 0.1$ would indicate that the cost of the herbicide treatment takes up 10% of what the gross profits of the crop

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would be if no weeds were present. It is clear to the point of trivial that for the use of the herbicide to be viable, the value of Ψ must be within the following boundaries:

$$0 \leq \Psi \leq 1$$

and in fact must be much closer to zero than 1, lest the cost of the herbicide application involve spending too much of the gross profit of the crop.

Thus, the solution of equation [A.1] now requires quantitative relationships involving yield loss. This solution is presented for two nonlinear representation of yield loss.

A.1 Yield Loss as Presented by Cousens (1985)

According to the convention of Cousens (1985) presented in the previous section, the yield losses above can be represented thus:

$$y_{L,n} = \frac{IN_w}{1 + IN_w / A} \qquad y_{L,h} = \frac{IN_w(1-\varepsilon_H)}{1 + IN_w(1-\varepsilon_H) / A}$$

where ε_H is the herbicidal efficacy:

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$$0 \le \varepsilon_H \le 1$$

and equation [A.1] now becomes:

$$\frac{IN_w}{1+\frac{IN_w}{A}} - \frac{IN_w(1-\varepsilon_H)}{1+\frac{IN_w(1-\varepsilon_H)}{A}} \ge \Psi$$

which can be manipulated thus:

$$\frac{AIN_w}{A+IN_w} - \frac{AIN_w(1-\varepsilon_H)}{A+IN_w(1-\varepsilon_H)} \ge \Psi$$

$$\frac{AIN_w[A+IN_w(1-\varepsilon_H)] - AIN_w(1-\varepsilon_H)(A+IN_w)}{(A+IN_w)[A+IN_w(1-\varepsilon_H)]} \ge \Psi$$

$$A^2IN_w + AI^2N_w^2 - AI^2N_w^2\varepsilon_H - A^2IN_w + A^2IN_w\varepsilon_H - AI^2N_w^2 + AI^2N_w^2\varepsilon_H \ge \Psi\left(A^2 + AIN_w - AIN_w\varepsilon_H + AIN_w + I^2N_w^2 - I^2N_w^2\varepsilon_H\right)$$

$$\left(A^2 + AIN_w + AIN_w - AIN_w\varepsilon_H + I^2N_w^2 - I^2N_w^2\varepsilon_H\right)\Psi - A^2IN_w\varepsilon_H \le 0$$

$$I^2\Psi(1-\varepsilon_H)N_w^2 + \left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]N_w + A^2\Psi \le 0 \qquad \text{[A.2]}$$

Solving for the boundaries inequality [A.2] involves a quadratic equation with the following solution:

$$N_{w\,EOL} = \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] \pm \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} \qquad \text{[A.3]}$$

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where equation [A.3] gives the EOT, the threshold weed density at which the use of the herbicide with the efficacy ε_H becomes viable. The fact that a "plus-or-minus" (±) symbol exists in the equation indicates that two such solutions exist, which separate three regions of weed density where economic viability must be investigated.

In addition, it is first noticed that in order for the above equation to have any real solutions, the expression under the radical must not be negative:

$$\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H) \geq 0 \qquad \text{[A.4]}$$

If the above is less than zero, then mathematically no real solutions exist, and thus no threshold weed density $N_{w,EOT}$ exists. From a weed management perspective it is reasonable to assert that such a threshold would cease to exist if the herbicide became so ineffective in controlling the weed that its use was never economically viable. Thus, by setting the above expression greater than or equal to zero we are for the moment seeking to quantify this threshold of herbicidal efficacy at which an EOT no longer exists. Solving the above equation for the herbicidal efficacy this becomes:

$$A^4I^2\varepsilon_H^2 - 2A^3I^2\varepsilon_H(2-\varepsilon_H)\Psi + A^2I^2(2-\varepsilon_H)^2\Psi^2 - 4A^2I^2\Psi^2(1-\varepsilon_H) \geq 0$$

$$A^4I^2\varepsilon_H^2 - 4A^3I^2\varepsilon_H\Psi + 2A^3I^2\varepsilon_H^2\Psi + 4A^2I^2\Psi^2 - 4A^2I^2\varepsilon_H\Psi^2 + A^2I^2\varepsilon_H^2\Psi^2 - 4A^2I^2\Psi^2 + 4A^2I^2\Psi^2\varepsilon_H \geq 0$$

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$$\left(A^4I^2+2A^3I^2\Psi+A^2I^2\Psi^2\right)\varepsilon_H^2+\left(-4A^3I^2\Psi-4A^2I^2\Psi^2+4A^2I^2\Psi^2\right)\varepsilon_H+4A^2I^2\Psi^2-4A^2I^2\Psi^2\geq 0$$

$$\left(A^4I^2+2A^3I^2\Psi+A^2I^2\Psi^2\right)\varepsilon_H^2-4A^3I^2\Psi\varepsilon_H\geq 0$$

Thus, this is again a quadratic inequality. Two solutions exist for the boundaries of this inequality. The first is trivial:

$$\varepsilon_H=0$$

and the second is solved thus:

$$\varepsilon_H=\frac{4A^3I^2\Psi}{A^4I^2+2A^3I^2\Psi+A^2I^2\Psi^2}=\frac{4A\Psi}{A^2+2A\Psi+\Psi^2}=\frac{4A\Psi}{(A+\Psi)^2}$$

Thus, three regions are herein defined:

Region 1

$$\varepsilon_H<0$$

Region 2

$$0<\varepsilon_H<\frac{4A\Psi}{(A+\Psi)^2}$$

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Region 3

$$\varepsilon_H > \frac{4A\Psi}{(A+\Psi)^2}$$

and each is tested for whether or not equation [A.4] is true. For region 1 the following test value is assigned:

$$\varepsilon_H = -\frac{4A\Psi}{(A+\Psi)^2}$$

creating a true statement:

$$\left(A^4I^2 + 2A^3I^2\Psi + A^2I^2\Psi^2\right)\left[-\frac{4A\Psi}{(A+\Psi)^2}\right]^2 - \left(4A^3I^2\Psi\right)\left[-\frac{4A\Psi}{(A+\Psi)^2}\right] \geq 0$$

Thus, region 1 is found to satisfy equation [A.4], although this region of negative herbicide efficacy is managerially inapplicable. For region 2 the following test value is assigned:

$$\varepsilon_H = \frac{2A\Psi}{(A+\Psi)^2}$$

with the following result:

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$$\left(A^4I^2+2A^3I^2\Psi+A^2I^2\Psi^2\right)\left[\frac{2A\Psi}{(A+\Psi)^2}\right]^2-\left(4A^3I^2\Psi\right)\left[\frac{2A\Psi}{(A+\Psi)^2}\right]$$

$$\left(A^2+2A\Psi+\Psi^2\right)\left[\frac{2A\Psi}{(A+\Psi)^2}\right]^2-\left(4A\Psi\right)\left[\frac{2A\Psi}{(A+\Psi)^2}\right]$$

$$\frac{4A^2\Psi^2-8A^2\Psi^2}{(A+\Psi)^2}=-\frac{4A^2\Psi^2}{(A+\Psi)^2}<0$$

Thus, region 2 is found to not satisfy equation [A.4]. For region 3 the following test value is assigned:

$$\varepsilon_H=\frac{5A\Psi}{(A+\Psi)^2}$$

with the following result:

$$\left(A^4I^2+2A^3I^2\Psi+A^2I^2\Psi^2\right)\left[\frac{5A\Psi}{(A+\Psi)^2}\right]^2-\left(4A^3I^2\Psi\right)\left[\frac{5A\Psi}{(A+\Psi)^2}\right]$$

$$\left(A^2+2A\Psi+\Psi^2\right)\left[\frac{5A\Psi}{(A+\Psi)^2}\right]^2-\left(4A\Psi\right)\left[\frac{5A\Psi}{(A+\Psi)^2}\right]$$

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$$\frac{25A^2\Psi^2 - 20A^2\Psi^2}{(A+\Psi)^2} = \frac{5A^2\Psi^2}{(A+\Psi)^2} \geq 0$$

Thus, region 3 is found to satisfy equation [A.4]. Thus, the minimum herbicidal efficacy is found in the boundary between regions 2 and 3:

$$\varepsilon_H \geq \frac{4A\Psi}{(A+\Psi)^2} \qquad [A.5]$$

Thus, there are instances in which no EOT is calculable. Equation [A.5] gives a minimum herbicidal efficacy for such a threshold to exist.

Returning to our fundamental equation [A.3] for EOT, we recall that, again, this involved the solution of a quadratic inequality. Thus, again three regions must be evaluated:

Region A

$$N_w < \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] - \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

Region B

$$\frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] - \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} < N_w < \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] + \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

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Region C

$$N_w > \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right] + \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2 - 4A^2 I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

where weed dynamics are suitable for control when equation [A.2] is satisfied. For region A we employ the following test value:

$$N_w = \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]}{I^2\Psi(1-\varepsilon_H)}$$

which when plugged into equation [A.2]:

$$I^2\Psi(1-\varepsilon_H)\frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{I^4\Psi^2(1-\varepsilon_H)^2} + \left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]\frac{-\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]}{I^2\Psi(1-\varepsilon_H)} + A^2\Psi \le 0$$

$$\frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{I^2\Psi(1-\varepsilon_H)} - \frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{I^2\Psi(1-\varepsilon_H)} + A^2\Psi \le 0$$

results in a false statement:

$$A^2\Psi \le 0$$

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Thus, weed densities in region A are not an economically viable situation for application of the herbicide. Similarly, when employing the following test value:

$$N_w = 0$$

region C is found very quickly to have an identical result:

$$A^2\Psi \le 0$$

This leaves the middle region B, where the following test value:

$$N_w = \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]}{2I^2\Psi(1-\varepsilon_H)}$$

results in the following:

$$I^2\Psi(1-\varepsilon_H)\frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{4I^4\Psi^2(1-\varepsilon_H)^2} + \left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]\frac{-\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]}{2I^2\Psi(1-\varepsilon_H)} + A^2\Psi \le 0$$

$$\frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{4I^2\Psi(1-\varepsilon_H)} - \frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{2I^2\Psi(1-\varepsilon_H)} + A^2\Psi \le 0$$

$$-\frac{\left[AI(2-\varepsilon_H)\Psi - A^2 I\varepsilon_H\right]^2}{4I^2\Psi(1-\varepsilon_H)} + A^2\Psi \le 0$$

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$$4I^2A^2\Psi^2(1-\varepsilon_H) \le \left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2$$

$$4A^2\Psi^2(1-\varepsilon_H) \le A^2(2-\varepsilon_H)^2\Psi^2 - 2A^3\varepsilon_H(2-\varepsilon_H)\Psi + A^4\varepsilon_H^2$$

$$4A^2\Psi^2 - 4A^2\Psi^2\varepsilon_H \le 4A^2\Psi^2 - 4A^2\Psi^2\varepsilon_H + A^2\Psi^2\varepsilon_H^2 - 4A^3\varepsilon_H\Psi + 2A^3\varepsilon_H^2\Psi + A^4\varepsilon_H^2$$

$$0 \le A^2\Psi^2\varepsilon_H^2 - 4A^3\varepsilon_H\Psi + 2A^3\varepsilon_H^2\Psi + A^4\varepsilon_H^2$$

$$0 \le \left(A^2\Psi^2 + 2A^3\Psi + A^4\right)\varepsilon_H^2 - 4A^3\varepsilon_H\Psi$$

$$0 \le \left(\Psi^2 + 2A\Psi + A^2\right)\varepsilon_H^2 - 4A\Psi\varepsilon_H$$

where the above is a repetition of requirements on ε_H that have been previously stated. Thus, again assuming that the herbicidal efficacy is such that the herbicide is potent enough, then region B describes the only range of weed densities for which control is financially warranted:

$$\frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] - \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} \le N \le \frac{-\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right] + \sqrt{\left[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H\right]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

[A.6]

Since this region is in the middle of two regions for which control is not financially viable suggests that there is not only a minimum density for viability of control, but also a *maximum* density for viable control. Apparently, this maximum

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threshold describes a point at which weed densities become so high that the yield loss even after using the herbicide is too great to support a crop. If such a result were found to be true for all managerial options, this latter threshold could potentially define the point at which the land would become a financial 'hopeless case' regarding weed control.

Thus, for an EOT to exist, the herbicidal efficacy must be above a certain threshold:

$$\varepsilon_H \geq \frac{4\Psi}{(\Psi+1)^2}$$

and the threshold density is defined thus:

$$\frac{-[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H] - \sqrt{[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)} < N_w < \frac{-[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H] + \sqrt{[AI(2-\varepsilon_H)\Psi - A^2I\varepsilon_H]^2 - 4A^2I^2\Psi^2(1-\varepsilon_H)}}{2I^2\Psi(1-\varepsilon_H)}$$

where

$$\Psi = \frac{C_h + C_a}{C_c Y_{wf}}$$

The results of the above solution are described in section 2.4.1.

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A.2 Solution for an Alternate form of the Yield Loss Equation

In addition, it must be noted that an alternate form of the yield equation exists from the introduction in the previous section:

$$Y_c = \frac{B_0}{1 + B_1 N_w}$$

where in particular it is visible that in this instance the weed density exists only in the denominator. Here the equations for proportional yield loss become:

$$y_{L,n} = 1 - \frac{1}{1 + B_1 N_w} \qquad y_{L,h} = 1 - \frac{1}{1 + B_1 (1 - \varepsilon_H) N_w}$$

and equation [A.1] now becomes:

$$\left(1 - \frac{1}{1 + B_1 N_w}\right) - \left[1 - \frac{1}{1 + B_1 (1 - \varepsilon_H) N_w}\right] \geq \Psi$$

which can be manipulated thus:

$$\frac{1}{1 + B_1 (1 - \varepsilon_H) N_w} - \frac{1}{1 + B_1 N_w} \geq \Psi$$

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$$\frac{B_1\varepsilon_H N_w}{[1+B_1(1-\varepsilon_H)N_w](1+B_1N_w)} \geq \Psi$$

$$\frac{B_1\varepsilon_H}{\Psi}N_w \geq 1 - B_1\varepsilon_H N_w + 2B_1N_w + (1-\varepsilon_H)B_1^2N_w^2$$

$$(1-\varepsilon_H)B_1^2N_w^2 + B_1\left[(2-\varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]N_w + 1 \leq 0 \qquad \text{[A.7]}$$

Again, the determination of the boundaries of inequality [A.7] involves solving a quadratic equation for N_w:

$$N_w = \frac{\frac{\varepsilon_H B_1}{\Psi} - (2-\varepsilon_H)B_1 \pm \sqrt{\left[(2-\varepsilon_H)B_1 - \frac{\varepsilon_H B_1}{\Psi}\right]^2 - 4(1-\varepsilon_H)B_1^2}}{2(1-\varepsilon_H)B_1^2}$$

which gives a value for the economic optimum threshold. The above equation can be simplified as follows:

$$N_w = \frac{\frac{\varepsilon_H}{\Psi} - (2-\varepsilon_H) \pm \sqrt{\left[(2-\varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1-\varepsilon_H)}}{2(1-\varepsilon_H)B_1} \qquad \text{[A.8]}$$

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Again, the expression under the radical must be positive:

$$\left[\left(2-\varepsilon_H\right)-\frac{\varepsilon_H}{\Psi}\right]^2-4\left(1-\varepsilon_H\right)\geq 0 \qquad \text{[A.9]}$$

or else no real solutions exist for N_w, and no optimum threshold exists. Again, two solutions exist for this threshold:

$$\left(2-\varepsilon_H\right)^2\Psi^2-2\left(2-\varepsilon_H\right)\Psi\varepsilon_H+\varepsilon_H^2-4\Psi^2+4\Psi^2\varepsilon_H\geq 0$$

$$4\Psi^2-4\varepsilon_H\Psi^2+\varepsilon_H^2\Psi^2-4\varepsilon_H\Psi+2\varepsilon_H^2\Psi+\varepsilon_H^2-4\Psi^2+4\varepsilon_H\Psi^2\geq 0$$

$$\left(\Psi^2+2\Psi+1\right)\varepsilon_H^2-4\Psi\varepsilon_H\geq 0$$

$$\left(\Psi+1\right)^2\varepsilon_H^2-4\Psi\varepsilon_H\geq 0$$

$$\varepsilon_H=0 \qquad\qquad \varepsilon_H=\frac{4\Psi}{\left(\Psi+1\right)^2}$$

and three regions are herein defined:

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Region 1

$$\varepsilon_H < 0$$

Region 2

$$0 < \varepsilon_H < \frac{4\Psi}{(\Psi+1)^2}$$

Region 3

$$\varepsilon_H > \frac{4\Psi}{(\Psi+1)^2}$$

and each is tested for whether or not equation [A.9] is true. For region 1 the following test value is assigned:

$$\varepsilon_H = -\frac{\Psi}{(\Psi+1)^2}$$

$$(1+\Psi)^2 \frac{\Psi^2}{(\Psi+1)^4} + 4\frac{\Psi^2}{(\Psi+1)^2} = 5\frac{\Psi^2}{(\Psi+1)^2} \geq 0$$

Thus, region 1 is found to satisfy equation [A.9]. For region 2 the following test value is assigned:

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$$\varepsilon_H = \frac{2\Psi}{(\Psi+1)^2}$$

$$4(1+\Psi)^2 \frac{\Psi^2}{(\Psi+1)^4} - 8\frac{\Psi^2}{(\Psi+1)^2} = -4\frac{\Psi^2}{(\Psi+1)^2} \leq 0$$

Thus, region 2 is found to not satisfy equation [A.9]. For region 3 the following test value is assigned:

$$\varepsilon_H = \frac{5\Psi}{(\Psi+1)^2}$$

$$25(1+\Psi)^2 \frac{\Psi^2}{(\Psi+1)^4} - 20\frac{\Psi^2}{(\Psi+1)^2} = 5\frac{\Psi^2}{(\Psi+1)^2} \geq 0$$

Thus, region 3 is found to satisfy equation [A.9]. Thus, the minimum herbicidal efficacy is visible from the inequality of region 3:

$$\varepsilon_H \geq \frac{4\Psi}{(\Psi+1)^2} \qquad [A.10]$$

Thus, as in the previous section, there are instances in which no EOT is calculable. Equation [A.10] gives a minimum herbicidal efficacy for this.

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Returning to our fundamental equation [A.8] for EOT, we see that, again, three regions must be evaluated:

Region A

$$N_w < \frac{\frac{\varepsilon_H}{\Psi} - (2-\varepsilon_H) - \sqrt{\left[(2-\varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1-\varepsilon_H)}}{2(1-\varepsilon_H)B_1}$$

Region B

$$\frac{\frac{\varepsilon_H}{\Psi} - (2-\varepsilon_H) - \sqrt{\left[(2-\varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1-\varepsilon_H)}}{2(1-\varepsilon_H)B_1} < N_w < \frac{\frac{\varepsilon_H}{\Psi} - (2-\varepsilon_H) + \sqrt{\left[(2-\varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1-\varepsilon_H)}}{2(1-\varepsilon_H)B_1}$$

Region C

$$N_w > \frac{\frac{\varepsilon_H}{\Psi} - (2-\varepsilon_H) + \sqrt{\left[(2-\varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1-\varepsilon_H)}}{2(1-\varepsilon_H)B_1}$$

where weed dynamics are suitable for control when inequality [A.7] is satisfied. For region A we employ the following test value:

$$N_w = 0$$

which does not result in inequality [A.7] being true. For region B we employ the test value:

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$$N_w = \frac{(\Psi+1)\varepsilon_H - 2}{2(1-\varepsilon_H)B_1}$$

which when plugged into inequality [A.7] results in:

$$(1-\varepsilon_H)B_1^2 \frac{[(\Psi+1)\varepsilon_H - 2]^2}{4(1-\varepsilon_H)^2 B_1^2} + B_1[2-(\Psi+1)\varepsilon_H]\frac{(\Psi+1)\varepsilon_H - 2}{2(1-\varepsilon_H)B_1} + 1 \le 0$$

$$\frac{[(\Psi+1)\varepsilon_H - 2]^2}{4(1-\varepsilon_H)} - \frac{[(\Psi+1)\varepsilon_H - 2]^2}{2(1-\varepsilon_H)} + 1 \le 0$$

$$\frac{[(\Psi+1)\varepsilon_H - 2]^2}{4(1-\varepsilon_H)} \ge 1$$

$$(\Psi+1)^2\varepsilon_H^2 - 4(\Psi+1)\varepsilon_H + 4 \ge 4 - 4\varepsilon_H$$

$$(\Psi+1)^2\varepsilon_H^2 - 4\Psi\varepsilon_H \ge 0$$

If it is assumed that $\varepsilon_H \ge 0$, then this equation becomes:

$$\varepsilon_H \ge \frac{4\Psi}{(\Psi+1)^2}$$

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which is identical to our previous findings for a minimal herbicidal efficacy for an EOT to exist. Thus, if one exists, then region B describes a range of weed densities for which control is financially warranted. For region C our test value is chosen to be:

$$N_w = \frac{(\Psi+1)\varepsilon_H - 2}{(1-\varepsilon_H)B_1}$$

With this test value inequality [A.7] becomes:

$$(1-\varepsilon_H)B_1^2 \frac{[(\Psi+1)\varepsilon_H - 2]^2}{(1-\varepsilon_H)^2 B_1^2} + B_1[2-(\Psi+1)\varepsilon_H]\frac{(\Psi+1)\varepsilon_H - 2}{(1-\varepsilon_H)B_1} + 1 \le 0$$

$$\frac{[(\Psi+1)\varepsilon_H - 2]^2}{(1-\varepsilon_H)} - \frac{[(\Psi+1)\varepsilon_H - 2]^2}{(1-\varepsilon_H)} + 1 \le 0$$

which results in the false statement that $1 \le 0$. Thus, region C describes a range of weed densities for which the use of the herbicide is not warranted. Interesting that this range involves weed densities greater than those of region B, a range where control has been deemed favorable. Apparently, region C describes a range of weed densities so high that the yield loss even after using the herbicide would be too great. If such a result were found to be true for all managerial options, the threshold between regions B and C could potentially define the point at which the land would become a financial 'hopeless case' regarding weed control.

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Thus, for the following depiction of yield loss in response to weed density:

$$Y_c = \frac{B_0}{1 + B_1 N_w}$$

for an EOT to exist, the herbicidal efficacy must be above a certain threshold:

$$\varepsilon_H \geq \frac{4\Psi}{(\Psi + 1)^2}$$

and the threshold is defined as:

$$\frac{\frac{\varepsilon_H}{\Psi} - (2 - \varepsilon_H) - \sqrt{\left[(2 - \varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1 - \varepsilon_H)}}{2(1 - \varepsilon_H)B_1} < N_w < \frac{\frac{\varepsilon_H}{\Psi} - (2 - \varepsilon_H) + \sqrt{\left[(2 - \varepsilon_H) - \frac{\varepsilon_H}{\Psi}\right]^2 - 4(1 - \varepsilon_H)}}{2(1 - \varepsilon_H)B_1}$$

where

$$\Psi = \frac{C_h + C_a}{C_c Y_{wf}}$$

Again, the results of the above solution are described in section 2.4.1.

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We have made a long mathematical journey to explore and quantify an aspect of pest management which is of fundamental importance – the existence of an economic threshold.

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A.3 References

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Appendix B

Equivalency of a Linear Dependence on Monthly Average Temperatures and a Linear Dependence on Monthly Thermal Degree Day Totals

Given any parameter y which is shown to display a linear dependence on thermal degree day totals:

$$y = \beta_0 + \beta_1 \sum_{i=1}^{n} (T_i - T_0)$$

where T_i is the mean daily temperature for day i in a month with n total days, T_0 is a threshold temperature, and β_0 and β_1 are parameters associated with analytical dependence or regression. The summation can be split into two components thus:

$$y = \beta_0 + \beta_1 \sum_{i=1}^{n} T_i - \beta_1 n T_0$$

where the second component can be simplified since T_0 is constant. This can be rearranged thus:

$$y = (\beta_0 - \beta_1 n T_0) + \beta_1 \sum_{i=1}^{n} T_i = (\beta_0 - \beta_1 n T_0) + \beta_1 n \left(\frac{1}{n} \sum_{i=1}^{n} T_i \right) = \alpha_0 + \alpha_1 \left(\frac{1}{n} \sum_{i=1}^{n} T_i \right)$$

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where the item in parentheses is monthly average temperature and α_0 and α_1 are constant parameters of an equivalent linear relationship:

$$\alpha_0 = \beta_0 - \beta_1 n T_0 \qquad \alpha_1 = \beta_1 n$$

In particular the equation for α_0 can be of use in the experimental calculation of a threshold temperature for an equivalent degree day model.

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Appendix C
ANOVA Tables for Optimal Models Relating Weed Density to Reciprocal Per-Plant Crop Yield

This appendix displays the full ANOVA tables for each of the optimal models chosen for each combination of crop and weed population observation timing in the third portion (Hypothesis 3) of the data analysis.. Note that the abbreviations 'GRS', 'BLF', 'VLC' respectively denote total grasses, total broadleaves, and volunteer corn.

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Corn and Early-Season Weed Populations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	12	0.00050402	0.00004200	15.20	<.0001
Error	67	0.00018517	0.00000276		
Corrected Total	79	0.00068919			

Root MSE	0.00166	R-Square	0.7313
Dependent Mean	0.00888	Adj R-Sq	0.6832
Coeff Var	18.72517		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.01379	0.00057553	23.96	<.0001
Y2000	1	-0.00510	0.00062069	-8.21	<.0001
Y2001	1	-0.00731	0.00084352	-8.67	<.0001
Y2002	1	-0.00831	0.00077456	-10.73	<.0001
AMARE	1	-0.00032254	0.00023223	-1.39	0.1695
CIRAR	1	0.00310	0.00228	1.36	0.1788
EPHDE	1	-0.00014686	0.00010778	-1.36	0.1776
HELAN	1	-0.00036761	0.00018788	-1.96	0.0546
POLAV	1	-0.00355	0.00277	-1.28	0.2043
SASKR	1	0.01758	0.00826	2.13	0.0371
GRS	1	-0.00005097	0.00001963	-2.60	0.0115
BLF	1	0.00011006	0.00003560	3.09	0.0029
VLC	1	0.00052712	0.00052443	1.01	0.3185

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Corn and Mid-Season Weed Populations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.00048693	0.00006087	21.37	<.0001
Error	71	0.00020226	0.00000285		
Corrected Total	79	0.00068919			

Root MSE	0.00169	R-Square	0.7065
Dependent Mean	0.00888	Adj R-Sq	0.6735
Coeff Var	19.01095		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.00621	0.00038220	16.24	<.0001
Y1999	1	0.00675	0.00059128	11.41	<.0001
Y2000	1	0.00238	0.00046239	5.15	<.0001
CIRAR	1	0.00342	0.00171	2.00	0.0497
DATST	1	-0.00510	0.00230	-2.21	0.0300
POLPY	1	0.03832	0.01832	2.09	0.0400
XANST	1	0.02668	0.02631	1.01	0.3141
GRS	1	-0.00013594	0.00005435	-2.50	0.0147
BLF	1	0.00010584	0.00003645	2.90	0.0049

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Corn and Late-Season Weed Populations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	0.00056078	0.00004006	20.28	<.0001
Error	65	0.00012841	0.00000198		
Corrected Total	79	0.00068919			

Root MSE	0.00141	R-Square	0.8137
Dependent Mean	0.00888	Adj R-Sq	0.7735
Coeff Var	15.83170		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.00850	0.00046910	18.12	<.0001
Y1999	1	0.00450	0.00064896	6.94	<.0001
Y2001	1	-0.00110	0.00056712	-1.93	0.0574
Y2002	1	-0.00251	0.00056787	-4.43	<.0001
AMARE	1	0.00141	0.00118	1.19	0.2377
CIRAR	1	-0.00182	0.00105	-1.74	0.0872
HELAN	1	0.00368	0.00072657	5.07	<.0001
LACSE	1	-0.00646	0.00365	-1.77	0.0818
MALNE	1	-0.03721	0.01849	-2.01	0.0483
PANMI	1	-0.03599	0.01464	-2.46	0.0166
POLCO	1	0.00032179	0.00012693	2.54	0.0137
POROL	1	0.05340	0.01865	2.86	0.0056
SOLNI	1	-0.00156	0.00062465	-2.51	0.0148
XANST	1	-0.01173	0.00263	-4.46	<.0001
VLC	1	-0.00458	0.00274	-1.67	0.0988

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Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.00467	0.00042458	6.70	0.0001
Error	20	0.00127	0.00006335		
Corrected Total	31	0.00594			

Root MSE	0.00796	R-Square	0.7866
Dependent Mean	0.06600	Adj R-Sq	0.6693
Coeff Var	12.06011		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.06323	0.00331	19.10	<.0001
Y1999	1	0.01049	0.00559	1.88	0.0753
ABUTH	1	0.00143	0.00114	1.26	0.2229
CIRAR	1	0.00264	0.00165	1.61	0.1242
DATST	1	0.04865	0.01337	3.64	0.0016
ECHCG	1	-0.03380	0.02295	-1.47	0.1563
EPHDE	1	-0.00235	0.00083791	-2.80	0.0111
HELAN	1	0.00384	0.00136	2.82	0.0106
KCHSC	1	0.00559	0.00103	5.43	<.0001
SETXX	1	-0.03394	0.02294	-1.48	0.1546
GRS	1	0.03367	0.02292	1.47	0.1575
BLF	1	-0.00046393	0.00020951	-2.21	0.0386

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Sugarbeets and Mid-Season Weed Populations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.00453	0.00064708	11.03	<.0001
Error	24	0.00141	0.00005866		
Corrected Total	31	0.00594			

Root MSE	0.00766	R-Square	0.7629
Dependent Mean	0.06600	Adj R-Sq	0.6937
Coeff Var	11.60514		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.05461	0.00324	16.86	<.0001
Y2001	1	0.00792	0.00362	2.19	0.0386
CHEAL	1	0.00200	0.00089180	2.24	0.0343
CIRAR	1	0.04451	0.01272	3.50	0.0018
KCHSC	1	0.00710	0.00220	3.22	0.0036
POLPY	1	0.07983	0.01616	4.94	<.0001
GRS	1	0.00290	0.00078917	3.68	0.0012
BLF	1	-0.00080027	0.00060932	-1.31	0.2015

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Sugarbeets and Late-Season Weed Populations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.00424	0.00060639	8.60	<.0001
Error	24	0.00169	0.00007052		
Corrected Total	31	0.00594			

Root MSE	0.00840	R-Square	0.7149
Dependent Mean	0.06600	Adj R-Sq	0.6318
Coeff Var	12.72492		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.05499	0.00365	15.08	<.0001
Y2001	1	0.00531	0.00425	1.25	0.2239
AMARE	1	-0.02045	0.00629	-3.25	0.0034
CHEAL	1	0.01306	0.00545	2.39	0.0248
DATST	1	0.19206	0.13592	1.41	0.1705
EPHDE	1	-0.05169	0.01639	-3.15	0.0043
SOLNI	1	0.00411	0.00255	1.61	0.1210
GRS	1	0.00624	0.00110	5.65	<.0001

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Wheat and Early-Season Observations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.00022574	0.00002822	22.09	0.0003
Error	7	0.00000894	0.00000128		
Corrected Total	15	0.00023469			

Root MSE	0.00113	R-Square	0.9619
Dependent Mean	0.02311	Adj R-Sq	0.9183
Coeff Var	4.89178		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.02137	0.00067166	31.81	<.0001
ABUTH	1	0.00031161	0.00010121	3.08	0.0178
AMARE	1	-0.00297	0.00085360	-3.47	0.0104
HELAN	1	0.00148	0.00026534	5.58	0.0008
POLCO	1	-0.00093741	0.00047196	-1.99	0.0874
SOLNI	1	-0.06221	0.01963	-3.17	0.0157
XANST	1	0.01373	0.00766	1.79	0.1159
GRS	1	0.00010189	0.00001204	8.46	<.0001
VLC	1	-0.02089	0.00364	-5.73	0.0007

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Wheat and Mid-Season Observations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.00021844	0.00003121	15.37	0.0005
Error	8	0.00001624	0.00000203		
Corrected Total	15	0.00023469			

Root MSE	0.00142	R-Square	0.9308
Dependent Mean	0.02311	Adj R-Sq	0.8702
Coeff Var	6.16687		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.02068	0.00069156	29.91	<.0001
ABUTH	1	0.00425	0.00099073	4.29	0.0027
CHEAL	1	0.00458	0.00117	3.91	0.0045
EPHDE	1	0.00485	0.00107	4.54	0.0019
HELAN	1	0.02311	0.00413	5.59	0.0005
KCHSC	1	0.00310	0.00079729	3.89	0.0046
XANST	1	-0.09742	0.03544	-2.75	0.0251
BLF	1	-0.00335	0.00084866	-3.94	0.0043

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Wheat and Late-Season Observations

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	0.00023185	0.00002318	40.82	0.0004
Error	5	0.00000284	5.679811E-7		
Corrected Total	15	0.00023469			

Root MSE	0.00075365	R-Square	0.9879
Dependent Mean	0.02311	Adj R-Sq	0.9637
Coeff Var	3.26163		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.02121	0.00039350	53.91	<.0001
AMARE	1	0.00920	0.00284	3.24	0.0230
DATST	1	0.81294	0.12999	6.25	0.0015
ECHCG	1	0.00122	0.00054761	2.23	0.0762
EPHDE	1	0.01133	0.00158	7.18	0.0008
HELAN	1	-0.04432	0.01332	-3.33	0.0209
KCHSC	1	-0.01865	0.00306	-6.09	0.0017
POLCO	1	-0.00319	0.00047847	-6.67	0.0011
SOLNI	1	0.01122	0.00401	2.80	0.0381
XANST	1	-0.12403	0.01744	-7.11	0.0009
GRS	1	-0.00071576	0.00022896	-3.13	0.0261

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Appendix D
Implementation of Reproductive Density

This appendix describes on a programmatic code and database design level the exact steps involved in the implementation of reproductive density in WISDEM. Twenty itemized modifications are given. (Visual Basic code is presented single spaced.)

1. The following fields have been added to the WEEDS table in Paramdb.mdb:

```
RepWeightType   (Char*3)
RepWeightRate   (Double)
RepWeightOffset (Double)
```

2. The following fields have been added to user-defined variable type Awdbio:

```
Type AWdBio
   id As String
   name As String
   MatureMonth As Integer
   MatureDay As Integer
   Emer1Parms As EmerParmSet
   Emer2Parms As EmerParmSet
   Prop_2 As Single
   D50 As Single
   MaxBiom As Single
   Amax As Single
   RepWeightType As String    'JRW 08/21/03 - Added for additional fields in ParamDB.Weeds
   RepWeightRate As Double    'JRW 08/21/03 - Added for additional fields in ParamDB.Weeds
   RepWeightOffset As Double  'JRW 08/21/03 - Added for additional fields in ParamDB.Weeds
End Type
```

3. The following fields have been added to user-defined variable type Aweed:

```
Type Aweed
   startday As Double
   startday_2 As Double
   emergestatus As Integer
   Emerged As Single
   LastEmerged As Single
   control As Single
   present As Single
   level As Integer
   Avalue As Single
   FirstAdate As Integer
   Aold As Single
```


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```
    weedcrop As Single
    ChngRate As Single
    RepDensity As Double        'JRW 08/21/03 - Added for Tracking of Reproductive Density
    CropCompWeight As Double    'JRW 02/18/04 - Added for Tracking of Crop Competitive Weighting
    CropCompDensity As Double   'JRW 02/17/04 - Added for Tracking of Crop Competitive Density
End Type
```

4. The following fields have been added to user-defined variable type A_YldBio:

```
Type A_YldBio
    Density As Single
    D50 As Single
    Avalue As Single
    RepDensity As Double        'JRW 08/21/03 - Added for Tracking of Reproductive Density
    CropCompDensity As Double   'JRW 02/17/04 - Added for Tracking of Crop Competitive Density
End Type
```

5. The following fields have been added to the WdEvents table in the user input database:

RepWeight	(Double)
RepDensity	(Single)
DaysFromCrem	(Integer)
LastDaysFromCrem	(Integer)

6. The following global variable has been added in modOverall to turn reproductive density on/off:

```
Public Const REPWEIGHTINGON As Boolean = True 'JRW 08/22/03 - Turns On/Off Reproductive Density
Weighting
```

7. A new procedure called Init_Reproductive_Weighting has been created:

```
Public Sub Init_Reproductive_Weighting(MuLabel As String)
    'This procedure populates the RepWeight fields of all appropriate records in
    'UserDB.WdEvents.  It is implemented with the following external adjustments:
    '   1.  The WEEDS table in ParamDB has three new fields -
    '           REPWEIGHTTYPE (Char*3) - Indicates linear (LIN) or exponential
    '                                   (EXP) Weighting
    '           REPWEIGHTRATE (Double) - Slope of Weighting
    '           REPWEIGHTOFFST (Double) - Day (after CREM event) at which weighting
    '                                     deviates from 1.
    '   2.  The Awdbio user-defined type now has three new components:
    '           RepWeightType (String)
    '           RepWeightRate (Double)
    '           RepWeightOffset (Double)
    '       which correspond to the new fields in adjustment 1.
    '   3.  In procedure Read_Wd_Biology the population of wdbio() has been expanded
    '       to include the fields listed in adjustment 2.
    '   4.  The following fields have been added to UserDB.WdEvents:
    '           DAYSFROMCREM (Integer)
    '           LASTDAYSFROMCREM (Integer)
    'P/F/GV Dependencies: Num_Spec
    'History:   JRW 08/21/03 - Initial Creation
    '         JRW 08/28/03 - Adding a section here where B_FR events are created
    '                        to clearly mark the starting point where weed fecundity
    '                        reduction is initiated.  Also enclosed all of second
    '                        half in BOF/EOF If/Then statement for enhanced stability
    'Comments:

    Dim strSQL As String
    Dim Rs_MuEvents As ADODB.Recordset
```


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```
Dim InSeason As Boolean
Dim CropEmergenceDate As Date
Dim DaysFromCrem As Integer
Dim LastDaysFromCrem As Integer
Dim I As Integer

'Open Recordset
strSQL = "SELECT * FROM WDEVENTS WHERE MULABEL = " & MuLabel
strSQL = strSQL & " AND PRIORITY < 98 ORDER BY DATE, PRIORITY, EVENTTYPE, INFO"
Set Rs_MuEvents = New ADODB.Recordset
Rs_MuEvents.Open strSQL, Db_user, adOpenDynamic, adLockOptimistic

'JRW 08/28/03 Adding this
'Search out CREM events here to create associated B_FR events
If Not (Rs_MuEvents.BOF And Rs_MuEvents.EOF) Then
   Rs_MuEvents.MoveFirst
   Do Until Rs_MuEvents.EOF
      If Rs_MuEvents.Fields("EVENTTYPE") = "CREM" Then
         CropEmergenceDate = Rs_MuEvents.Fields("DATE")
         For I = 1 To Num_Spec
            Rs_MuEvents.AddNew
            Rs_MuEvents.Fields("MULABEL") = MU(This_MU)
            Rs_MuEvents.Fields("DATE") = CropEmergenceDate + wdbio(I).RepWeightOffset
            Rs_MuEvents.Fields("PRIORITY") = 9
            Rs_MuEvents.Fields("EVENTTYPE") = "B_FR"
            Rs_MuEvents.Fields("INFO") = wdbio(I).id
            Rs_MuEvents.Fields("INFO2") = "Begin fecundity reduction for " & wdbio(I).id
            Rs_MuEvents.Fields("STRINGINFO") = "NA"
            Rs_MuEvents.Update
         Next I
      End If
      Rs_MuEvents.MoveNext
   Loop
End If
Rs_MuEvents.Requery

   'Search out dates in season and record information in DAYSFROMCREM AND LASTDAYSFROMCREM
fields
   If Not (Rs_MuEvents.BOF And Rs_MuEvents.EOF) Then
      Rs_MuEvents.MoveFirst
      InSeason = False
      Do Until Rs_MuEvents.EOF
         If Rs_MuEvents.Fields("EVENTTYPE") = "CREM" Then
            InSeason = True
            CropEmergenceDate = Rs_MuEvents.Fields("DATE")
            LastDaysFromCrem = 0
         Else
            If Rs_MuEvents.Fields("EVENTTYPE") = "HARV" Then
               InSeason = False
            Else
               If InSeason Then
                  DaysFromCrem = Rs_MuEvents("DATE") - CropEmergenceDate
                  Rs_MuEvents("DAYSFROMCREM") = DaysFromCrem
                  Rs_MuEvents("LASTDAYSFROMCREM") = LastDaysFromCrem
                  Rs_MuEvents.Update
                  LastDaysFromCrem = DaysFromCrem
               End If
            End If
         End If
         Rs_MuEvents.MoveNext
      Loop
   End If

   Rs_MuEvents.Close
   Set Rs_MuEvents = Nothing
```


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```
End Sub
```

8. In the Read_Wd_Biology subroutine, statements have been added to populate the new elements of the wdbio array:

```
wdbio(ispec).MaxBiom = Tb_weeds("MaxBiom")
wdbio(ispec).D50 = Tb_weeds("D50")
wdbio(ispec).Prop_2 = Tb_weeds("Prop2")

'JRW 08/21/03 - Adding these lines with the added fields in ParamDB.Weeds
wdbio(ispec).RepWeightType = Tb_weeds("REPWEIGHTTYPE")
wdbio(ispec).RepWeightRate = Tb_weeds("REPWEIGHTRATE")
wdbio(ispec).RepWeightOffset = Tb_weeds("REPWEIGHTOFFSET")

If wdbio(ispec).Prop_2 > zero Then
   wdbio(ispec).Emer2Parms.EmerMonth = Tb_weeds("Emer2Month")
   wdbio(ispec).Emer2Parms.EmerDay = Tb_weeds("Emer2Day")
   wdbio(ispec).Emer2Parms.EmerPar2 = Tb_weeds("Emer2Par2")
   wdbio(ispec).Emer2Parms.EmerPar3 = Tb_weeds("Emer2Par3")
Else
   wdbio(ispec).Prop_2 = zero
End If
```

9. In the Simulate_Events subroutine, statements have been added to read in the DaysFromCrem and LastDaysFromCrem variables from the WdEvents table.

```
'Read information for the event
Event_Date = Rs_MuEvents("DATE")
event_type = Rs_MuEvents("EVENTTYPE")
stringinfo$ = Rs_MuEvents("STRINGINFO")
info$ = Rs_MuEvents("INFO")
info2$ = Rs_MuEvents("INFO2")
info3! = Rs_MuEvents("INFO3")

'JRW 08/22/03 - Added as part of reproductive density implementation
DaysFromCrem = Rs_MuEvents("DAYSFROMCREM")
LastDaysFromCrem = Rs_MuEvents("LASTDAYSFROMCREM")

'JRW 08/29/03 - Adding additional reporting
Call frmMDIParent.stbMsg("For '" & MU(This_MU) & "': Simulating " & Event_Date)

'Set efficacy for this event to zero
For ispec = 1 To Num_Spec
   eff(ispec) = 0
Next ispec
```

10. In the Simulate_Events subroutine, calls to Tillage_Operation, Post_Control, and Crop_Harvest_Weeds have been updated to include the variables DaysFromCrem and LastDaysFromCrem in the procedure calls:

```
'Tillage operation
Case "TILL"
   'JRW 08/22/03 - Modifying this as part of reproductive density implementation
   'Call Tillage_Operation(info$, eff())
   Call Tillage_Operation(info$, eff(), DaysFromCrem, LastDaysFromCrem)

'Postemergence Herbicide application
Case "POST"
   'JRW 08/22/03 - Modifying this as part of reproductive density implementation
   'Call Post_Control(info$, eff())
   Call Post_Control(info$, eff(), DaysFromCrem, LastDaysFromCrem)
```


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```
        'Crop harvest
        Case "HARV"
           'JRW 08/22/03 - Modifying this as part of reproductive density implementation
           'Call Crop_Harvest_Weeds(eff(), muid$, Event_Date, curcrop)
           Call Crop_Harvest_Weeds(eff(), muid$, Event_Date, CurCrop, DaysFromCrem,
LastDaysFromCrem)
```

11. A new procedure called GetRepWeight has been created:

```
Public Function GetRepWeight(ispec As Integer, DaysFromCrem As Integer, LastDaysFromCrem As
Integer)
   'This function returns the weighting of a specific cohort from competitive density
   'to reproductive density
   'P/F/GV Dependencies:
   'History:   JRW 08/21/03 - Initial Creation
   '          JRW 08/28/03 - Added a watch for instances where DaysFromCrem is less than
   '                    offset value
   'Comments:

   If Not REPWEIGHTINGON Then
      GetRepWeight = 1
      Exit Function
   End If

   If DaysFromCrem = LastDaysFromCrem Then
      GetRepWeight = 1
      Exit Function
   End If

   'JRW 08/28/03 - Adding this section
   If DaysFromCrem <= wdbio(ispec).RepWeightOffset Then
      GetRepWeight = 1
      Exit Function
   End If

   If wdbio(ispec).RepWeightType = "LIN" Then
      GetRepWeight = 1 - 0.5 * wdbio(ispec).RepWeightRate * (DaysFromCrem +
LastDaysFromCrem)
      GetRepWeight = GetRepWeight - wdbio(ispec).RepWeightRate * wdbio(ispec).RepWeightOffset
      If GetRepWeight < 0 Then GetRepWeight = 0
   Else
      If wdbio(ispec).RepWeightType = "EXP" Then
         GetRepWeight = Exp(-1 * wdbio(ispec).RepWeightRate * LastDaysFromCrem)
         GetRepWeight = GetRepWeight - Exp(-1 * wdbio(ispec).RepWeightRate * DaysFromCrem)
         GetRepWeight = GetRepWeight * Exp(wdbio(ispec).RepWeightRate *
wdbio(ispec).RepWeightOffset)
         GetRepWeight = GetRepWeight / wdbio(ispec).RepWeightRate
         GetRepWeight = GetRepWeight / (DaysFromCrem - LastDaysFromCrem)
      End If
   End If

End Function
```

12. In the Tillage_Operation subroutine, the call to Update_Gen_Control was updated to include the variables DaysFromCrem and LastDaysFromCrem in the procedure call:

```
   'Calculate control
   'JRW 08/22/03 - Modifying this as part of the implementation of reproductive density
   'Call Update_Gen_Control(eff(ispec), ispec, "TILL")
   Call Update_Gen_Control(eff(ispec), ispec, "TILL", DaysFromCrem, LastDaysFromCrem)
```


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13. In the Post_Control subroutine, the call to Update_Gen_Control was updated to include the variables DaysFromCrem and LastDaysFromCrem in the procedure call:

```
'JRW 08/22/03 - Adding parameters for inclusion of reproductive density
'Call Update_Gen_Control(eff(ispec), ispec, "POST")
Call Update_Gen_Control(eff(ispec), ispec, "POST", DaysFromCrem, LastDaysFromCrem)
```

14. In the Crop_Harvest_Weeds subroutine, the call to Update_Gen_Control was updated to include the variables DaysFromCrem and LastDaysFromCrem in the procedure call:

```
'Calculate control
'JRW 08/22/03 - Modifying this as part of reproductive density implementation
'Call Update_Gen_Control(eff(ispec), ispec, "HARV")
Call Update_Gen_Control(eff(ispec), ispec, "HARV", DaysFromCrem, LastDaysFromCrem)
```

15. The Update_Gen_Control procedure now updates the RepDensity field of the Weeds array via a call to GetRepWeight:

```
'Calculate control
Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control
Weeds(ispec).control = Weeds(ispec).control + Weeds(ispec).present * teff
'Weeds(ispec).control = Weeds(ispec).control + Weeds(ispec).present * CSng(effispec) / 100#
Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control
Weeds(ispec).Avalue = Weeds(ispec).Avalue * (1 - teff)
'Weeds(ispec).Avalue = Weeds(ispec).Avalue * (1 - CSng(effispec) / 100#)

'JRW 08/22/03 - Adding this with implementation of reproductive density
Weeds(ispec).RepDensity = Weeds(ispec).RepDensity * (1 - teff) + (Weeds(ispec).Emerged -
Weeds(ispec).LastEmerged) * (1 - teff) * GetRepWeight(ispec, DaysFromCrem, LastDaysFromCrem)
```

16. The Update_SA_Control procedure now updates the RepDensity field of the Weeds array via a call to GetRepWeight:

```
'Update control
controlled = (Weeds(ispec).Emerged - Weeds(ispec).LastEmerged) * Total_Eff
Weeds(ispec).control = Weeds(ispec).control + controlled
Weeds(ispec).Avalue = Weeds(ispec).Aold + (Weeds(ispec).Avalue - Weeds(ispec).Aold) * (1 -
Total_Eff)
Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control

'JRW 08/22/03 - Including this as part of reproductive density implementation
Weeds(ispec).RepDensity = Weeds(ispec).RepDensity + (Weeds(ispec).Emerged -
Weeds(ispec).LastEmerged) * (1 - Total_Eff) * GetRepWeight(ispec, DaysFromCrem,
LastDaysFromCrem)

'JRW 02/18/04 - Adding this with the implementation of Crop Competitive Density
Weeds(ispec).CropCompWeight = GetCompWeight(DaysFromCrem, LastDaysFromCrem,
CurCrop)
Weeds(ispec).CropCompDensity = Weeds(ispec).CropCompDensity + (Weeds(ispec).present +
0.5 * (Weeds(ispec).Emerged - Weeds(ispec).LastEmerged) * (1 - Total_Eff)) *
Weeds(ispec).CropCompWeight
```


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17. The Simulate_Events procedure now updates the RepDensity field of the Weeds array when no control is occurring:

```
    If Event_Date <> Last_Event_Date Then
      If Num_Active_SA > 0 Then
        Call Update_SA_Control(Event_Date, Emerg_day(), CurCrop, info2$, DaysFromCrem,
LastDaysFromCrem)
      Else

        'JRW 02/18/04 - Adding this with the implementation of Crop Competitive Density
        'JRW 02/21/04 - Correction to third line - replacement of Weeds().present with (emerged -
controlled)
        For ispec = 1 To Num_Spec
          Weeds(ispec).CropCompWeight = GetCompWeight(DaysFromCrem, LastDaysFromCrem,
CurCrop)
          Weeds(ispec).CropCompDensity = Weeds(ispec).CropCompDensity +
(Weeds(ispec).LastEmerged - Weeds(ispec).control + 0.5 * (Weeds(ispec).Emerged -
Weeds(ispec).LastEmerged)) * Weeds(ispec).CropCompWeight
        Next ispec

        If event_type <> "TILL" And event_type <> "POST" And event_type <> "HARV" Then
          For ispec = 1 To Num_Spec
            Weeds(ispec).RepDensity = Weeds(ispec).RepDensity + (Weeds(ispec).Emerged -
Weeds(ispec).LastEmerged) * GetRepWeight(ispec, DaysFromCrem, LastDaysFromCrem)
          Next ispec
        End If
      End If
    End If
```

18. In the Weed_Death subroutine, a statement was added to reset the RepDensity field in the Weeds() array for the present weed:

```
    Weeds(I).emergestatus = I_zero
    Weeds(I).Emerged = I_zero
    Weeds(I).control = I_zero
    Weeds(I).present = I_zero
    Weeds(I).ChngRate = No_data

    'JRW 08/22/03 - Implementation of Reproductive Density
    Weeds(I).RepDensity = I_zero

    'JRW 02/21/04 - Removed this as it is deemed incorrect
    'JRW 02/18/04 - Implementation of Crop Competitive Density
    'Weeds(I).CropCompWeight = I_zero
    'JRW 02/17/04 - Implementation of Crop Competitive Density
    'Weeds(I).CropCompDensity = I_zero
```

19. The Fill_YldBio procedure initializes the RepDensity field of the YldBio array with the other fields in the YldBio array:

```
  Select Case CurCrop.id

    Case "FALLW"
      For ispec = 1 To Num_Spec
        Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control
        Weeds(ispec).present = Weeds(ispec).present * Find_Current_Pop(ispec)

        'Fill YldBio with appropriate information.
        YldBio(ispec).Avalue = wdbio(ispec).Amax
        YldBio(ispec).Density = Weeds(ispec).present
```


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```
            YldBio(ispec).D50 = wdbio(ispec).D50

            'JRW 08/22/03 - Adding this with reproductive density implementation
            YldBio(ispec).RepDensity = Weeds(ispec).RepDensity * Find_Current_Pop(ispec)

            'JRW 02/17/04 - Adding this with the implementation of crop competitive density
            YldBio(ispec).CropCompDensity = Weeds(ispec).CropCompDensity *
Find_Current_Pop(ispec)

         Next ispec

         YldBio(0).Avalue = 0
         YldBio(0).Density = 0
         YldBio(0).D50 = 1

         'JRW 08/22/03 - Adding this with reproductive density implementation
         YldBio(0).RepDensity = 0

         'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
         YldBio(0).CropCompDensity = 0

      Case Else
         For ispec = 1 To Num_Spec
            Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control
            propalive = Weeds(ispec).present  'This is for the sole purpose of adjusting Avalue below
            Weeds(ispec).present = Weeds(ispec).present * Find_Current_Pop(ispec)

            'Fill YldBio with appropriate information.
            If Weeds(ispec).Avalue <> 0 And propalive <> 0 Then YldBio(ispec).Avalue =
Weeds(ispec).Avalue / propalive Else YldBio(ispec).Avalue = 0
            YldBio(ispec).Density = Weeds(ispec).present
            YldBio(ispec).D50 = wdbio(ispec).D50

            'JRW 08/22/03 - Adding this with reproductive density implementation
            YldBio(ispec).RepDensity = Weeds(ispec).RepDensity * Find_Current_Pop(ispec)

            'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
            YldBio(ispec).CropCompDensity = Weeds(ispec).CropCompDensity *
Find_Current_Pop(ispec)

         Next ispec

         YldBio(0).Avalue = 1
         YldBio(0).Density = CurCrop.Density
         YldBio(0).D50 = CurCrop.D50

         'JRW 08/22/03 - Adding this with reproductive density implementation
         YldBio(0).RepDensity = CurCrop.Density

         'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
         YldBio(0).CropCompDensity = CurCrop.Density

   End Select
```

20. The YieldOf procedure now uses the RepDensity field of the YldBio array in the prescribed manner:

```
         'JRW 08/22/03 - Modifying this to look at reproductive density
         'cloadp2num = YldBio(ix).Density * CI(ix) 'that's all
         cloadp2num = YldBio(ix).RepDensity * CI(ix) 'that's all
         cloadp2den = YldBio(Uno).D50
         cloadp3num = YldBio(Uno).D50
         cloadp3den = YldBio(Uno).D50
```


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Appendix E
Implementation of Crop Competitive Density

This appendix describes on a programmatic code and database design level the exact steps involved in the implementation of crop competitive density in WISDEM. Sixteen itemized modifications are given. (Visual Basic code is presented single spaced.)

1. In the paramdb.mdb database, two new fields were added and populated in the CBIO table:

REMK	(Double)
REMA	(Double)

2. In the paramdb.mdb database, settings in the COMP field were modified in the CBIO table. This, combined with the settings in the new fields described in the previous item are displayed below:

CBIO

CROPID	CROPTYPE	COMP	REMK	REMA
DCORN	Corn (DL)	114	0.066	0.0147
DCOTN	Cotton (DL)	0	0.066	0.0147
DSOYB	Soybeans (DL)	105	0.066	0.0147
DSUNF	Sunflower (DL)	112	0.066	0.0147
FALLW	Fallow	0	0.066	0.0147
FMILL	Foxtail Millet (DL)	92	0.0825	0.0147
ICORN	Corn (IR)	114	0.066	0.0147
ICOTN	Cotton (IR)	0	0.066	0.0147
IFMIL	Foxtail Millet (IR)	92	0.0825	0.0147
IPMIL	Proso Millet (IR)	92	0.0825	0.0147
IRWHT	Winter Wheat (IR)	210	0.066	0.0147
ISOYB	Soybeans (IR)	105	0.066	0.0147
ISUNF	Sunflower (IR)	112	0.066	0.0147
PMILL	Proso Millet (DL)	92	0.0825	0.0147
WIWHT	Winter Wheat (DL)	210	0.066	0.0147

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3. In the A_Crop user-defined variable type, the following fields were added:

```
Type A_Crop
   id As String
   Density As Single
   croptype As String
   tilltype As String
   irrtype As Integer
   yld_loss As Single
   k As Single
   D50 As Single
   MaxBiom As Single
   HarvEff As Integer
   EmergeDays As Integer
   SDPG As Single
   DaysToComp As Integer
   Rem_k As Double          'JRW 02/17/04 - Added as part of crop competitive density implementation
   Rem_a As Double          'JRW 02/17/04 - Added as part of crop competitive density implementation
End Type
```

4. In the Init_Crop_Bio procedure, the following statements were added to populate additional fields in the Crops array:

```
   'Make "zero'th" entry in Crops array Fallow, in case it gets invoked without
   'being in cropdat;
   icrop = 0
   Crops(icrop).croptype = "Fallow"
   Crops(icrop).irrtype = 0
   Crops(icrop).id = "FALLW"
   Crops(icrop).Density = 0 'Default Density.
   Crops(icrop).D50 = 1
   Crops(icrop).HarvEff = 0
   Crops(icrop).k = 1
   Crops(icrop).MaxBiom = 0
   Crops(icrop).EmergeDays = 1
   Crops(icrop).SDPG = 0
   Crops(icrop).DaysToComp = 0
   Crops(icrop).Rem_a = 0        'JRW 02/17/04 - Added as part of Crop Competitive Density
Implementation
   Crops(icrop).Rem_k = 0        'JRW 02/17/04 - Added as part of Crop Competitive Density
Implementation

         Crops(icrop).croptype = Dy_crops("CROPTYPE")
         Crops(icrop).irrtype = Dy_crops("IRRIGATION")
         'irrcount = irrcount + Dy_crops("IRRIGATION")
         If Dy_crops("IRRIGATION") = 1 Then MUIRRTYPE = 1  'this replaces previous line, takes more
time but less memory...
         Crops(icrop).id = Tb_cbio("CROPID")
         Crops(icrop).Density = Tb_cbio("DENSITY") 'Default Density.
         Crops(icrop).D50 = Tb_cbio("D50")
         Crops(icrop).HarvEff = Tb_cbio("Harveff")
         Crops(icrop).k = Tb_cbio("K")
         Crops(icrop).MaxBiom = Tb_cbio("MAXBIOM")
         Crops(icrop).EmergeDays = Tb_cbio("EMERGEDAYS")
         Crops(icrop).SDPG = Tb_cbio("SEEDSPERGRAM")
         Crops(icrop).DaysToComp = Tb_cbio("COMP")
         Crops(icrop).Rem_a = Tb_cbio("REMA")   'JRW 02/17/04 - Added as part of Crop Competitive
Density Implementation
         Crops(icrop).Rem_k = Tb_cbio("REMK")   'JRW 02/17/04 - Added as part of Crop Competitive
Density
```


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5. The following global variable was created to turn crop competitive density on/off:

```
Public Const CROPCOMPDENSITYON As Boolean = True 'JRW 02/17/04 - Turns On/Off Crop Competitive
Denstiy Weighting
```

6. A new function called CropIsVulnerable has been created:

```
Public Function CropIsVulnerable(DaysFromCrem As Integer, CremToComp As Integer) As Boolean
   'Returns whether or not an event is between a CREM and a COMP event.
   'This is whether or not it is occurring within the critical competitive
   'period of the crop.
   'P/F/GV Dependencies:
   'History:  JRW 02/17/04 - Initial Creation
   'Comments:

   If DaysFromCrem <= CremToComp And DaysFromCrem > 0 Then
      CropIsVulnerable = True
   Else
      CropIsVulnerable = False
   End If

End Function
```

7. A new function called GetCompWeight has been created:

```
Public Function GetCompWeight(DaysFromCrem As Integer, LastDaysFromCrem, CurCrop As A_Crop) As
Double
   'Returns a competitive weight for the calculation of crop competitive density
   'P/F/GV Dependencies:  CropIsVulnerable   A_Crop
   'History:  JRW 02/17/04 - Initial Creation
   'Comments:

   Dim CremToComp As Integer
   CremToComp = CurCrop.DaysToComp - CurCrop.EmergeDays

   If Not CropIsVulnerable(DaysFromCrem, CremToComp) Then
      GetCompWeight = 0
      Exit Function
   End If

   If Not CROPCOMPDENSITYON Then
      GetCompWeight = 1
      Exit Function
   End If

   If DaysFromCrem = LastDaysFromCrem Then
      GetCompWeight = 1
      Exit Function
   End If

   GetCompWeight = (CurCrop.Rem_a * Exp(CurCrop.Rem_k * DaysFromCrem) - CurCrop.Rem_a) /
(CurCrop.Rem_a * Exp(CurCrop.Rem_k * DaysFromCrem) + 1)
   GetCompWeight = GetCompWeight - (CurCrop.Rem_a * Exp(CurCrop.Rem_k * LastDaysFromCrem) -
CurCrop.Rem_a) / (CurCrop.Rem_a * Exp(CurCrop.Rem_k * LastDaysFromCrem) + 1)
   GetCompWeight = GetCompWeight * (CurCrop.Rem_a * Exp(CurCrop.Rem_k * CremToComp) + 1) /
(CurCrop.Rem_a * Exp(CurCrop.Rem_k * CremToComp) - CurCrop.Rem_a)

End Function
```


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8. In the A_Weed user-defined variable type, the following fields were added:

```
Type Aweed
   startday As Double
   startday_2 As Double
   emergestatus As Integer
   Emerged As Single
   LastEmerged As Single
   control As Single
   present As Single
   level As Integer
   Avalue As Single
   FirstAdate As Integer
   Aold As Single
   weedcrop As Single
   ChngRate As Single
   RepDensity As Double        'JRW 08/21/03 - Added for Tracking of Reproductive Density
   CropCompWeight As Double    'JRW 02/18/04 - Added for Tracking of Crop Competitive Weighting
   CropCompDensity As Double   'JRW 02/17/04 - Added for Tracking of Crop Competitive Density
End Type
```

9. In the Emerge_Crop procedure the following statements were added for updating the additional fields in the Weeds array:

```
'JRW 02/21/04 - Adding this for the implementation of CropCompDensity
For ispec = 1 To Num_Spec
   Weeds(ispec).CropCompDensity = Dbl_zero
   Weeds(ispec).CropCompWeight = Dbl_zero
Next ispec
```

10. In the Simulate_Events procedure statements were added for updating the additional fields in the Weeds array:

11. In the Update_SA_Control procedure statements were added for updating the additional fields in the Weeds array:

```
'Update control
controlled = (Weeds(ispec).Emerged - Weeds(ispec).LastEmerged) * Total_Eff
Weeds(ispec).control = Weeds(ispec).control + controlled
Weeds(ispec).Avalue = Weeds(ispec).Aold + (Weeds(ispec).Avalue - Weeds(ispec).Aold) * (1 -
Total_Eff)
Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control

'JRW 08/22/03 - Including this as part of reproductive density implementation
Weeds(ispec).RepDensity = Weeds(ispec).RepDensity + (Weeds(ispec).Emerged -
Weeds(ispec).LastEmerged) * (1 - Total_Eff) * GetRepWeight(ispec, DaysFromCrem, LastDaysFromCrem)

'JRW 02/18/04 - Adding this with the implementation of Crop Competitive Density
Weeds(ispec).CropCompWeight = GetCompWeight(DaysFromCrem, LastDaysFromCrem, CurCrop)
Weeds(ispec).CropCompDensity = Weeds(ispec).CropCompDensity + (Weeds(ispec).present + 0.5 *
(Weeds(ispec).Emerged - Weeds(ispec).LastEmerged) * (1 - Total_Eff)) * Weeds(ispec).CropCompWeight
```


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12. In the user input database the following fields were added to the WDEVENTS table:

CROPCOMPWEIGHT	(Double)
CROPCOMPDENSITY	(Double)

13. In the Write_TempSim procedure additional statements were added for writing information to the new fields in the WDEVENTS table:

```
'JRW 02/18/04 - Adding this with the implementation of Crop Competitive Density
Tb_events("CROPCOMPWEIGHT") = Weeds(ispec).CropCompWeight

'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
Tb_events("CROPCOMPDENSITY") = Weeds(ispec).CropCompDensity
```

14. In the A_YldBio user-defined variable type, the following field was added:

```
Type A_YldBio
   Density As Single
   D50 As Single
   Avalue As Single
   RepDensity As Double        'JRW 08/21/03 - Added for Tracking of Reproductive Density
   CropCompDensity As Double   'JRW 02/17/04 - Added for Tracking of Crop Competitive Density
End Type
```

15. In the Fill_YldBio procedure, population of the new field in the YldBio array was added:

```
Select Case CurCrop.id

  Case "FALLW"
     For ispec = 1 To Num_Spec
        Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control
        Weeds(ispec).present = Weeds(ispec).present * Find_Current_Pop(ispec)

        'Fill YldBio with appropriate information.
        YldBio(ispec).Avalue = wdbio(ispec).Amax
        YldBio(ispec).Density = Weeds(ispec).present
        YldBio(ispec).D50 = wdbio(ispec).D50

        'JRW 08/22/03 - Adding this with reproductive density implementation
        YldBio(ispec).RepDensity = Weeds(ispec).RepDensity * Find_Current_Pop(ispec)

        'JRW 02/17/04 - Adding this with the implementation of crop competitive density
        YldBio(ispec).CropCompDensity = Weeds(ispec).CropCompDensity * Find_Current_Pop(ispec)

     Next ispec

     YldBio(0).Avalue = 0
     YldBio(0).Density = 0
     YldBio(0).D50 = 1

     'JRW 08/22/03 - Adding this with reproductive density implementation
     YldBio(0).RepDensity = 0

     'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
     YldBio(0).CropCompDensity = 0

  Case Else
     For ispec = 1 To Num_Spec
```


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```
            Weeds(ispec).present = Weeds(ispec).Emerged - Weeds(ispec).control
            propalive = Weeds(ispec).present  'This is for the sole purpose of adjusting Avalue below
            Weeds(ispec).present = Weeds(ispec).present * Find_Current_Pop(ispec)

            'Fill YldBio with appropriate information.
            If Weeds(ispec).Avalue <> 0 And propalive <> 0 Then YldBio(ispec).Avalue =
Weeds(ispec).Avalue / propalive Else YldBio(ispec).Avalue = 0
            YldBio(ispec).Density = Weeds(ispec).present
            YldBio(ispec).D50 = wdbio(ispec).D50

            'JRW 08/22/03 - Adding this with reproductive density implementation
            YldBio(ispec).RepDensity = Weeds(ispec).RepDensity * Find_Current_Pop(ispec)

            'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
            YldBio(ispec).CropCompDensity = Weeds(ispec).CropCompDensity * Find_Current_Pop(ispec)

        Next ispec

        YldBio(0).Avalue = 1
        YldBio(0).Density = CurCrop.Density
        YldBio(0).D50 = CurCrop.D50

        'JRW 08/22/03 - Adding this with reproductive density implementation
        YldBio(0).RepDensity = CurCrop.Density

        'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
        YldBio(0).CropCompDensity = CurCrop.Density

    End Select
```

16. In the YieldOf procedure, if CROPCOMPDENSITYON is True and the yield is being calculated for the crop and not a weed (ix = 0), then crop competitive densities are used for all of the weeds:

```
    'JRW 02/17/04 - Adding this with the implementation of Crop Competitive Density
    If CROPCOMPDENSITYON = True And ix = 0 Then
       For ispec = 1 To Num_Spec
          YldBio(ispec).Density = YldBio(ispec).CropCompDensity
       Next ispec
    End If
```


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Appendix F
Implementation of ActiveX Data Objects (ADO)

On a fundamental level the upgrade to ADO is exemplified in the following fundamental declarations taken from the modDataMgt module:

```
Public Db_param As ADODB.Connection
Public Db_events As ADODB.Connection
Public Db_user As ADODB.Connection
Public Db_output As ADODB.Connection

Public Tb_eventsav As ADODB.Recordset
Public Tb_weedsav As ADODB.Recordset
Public Tb_crophbsav As ADODB.Recordset

Public Tb_events As ADODB.Recordset
Public Tb_gpfyldloss As ADODB.Recordset
Public Tb_weedcrop As ADODB.Recordset
Public Tb_weedpop As ADODB.Recordset
Public Tb_monthpress As ADODB.Recordset
```

as well as in the following:

```
Public Sub Init_databases()

   'JRW 07/08/03 - Adding this informative message
   Call frmMDIParent.stbMsg("Initializing database variables...")

   Set Db_param = New ADODB.Connection
   Db_param.Open gstrCnn & file_param$
   Set Db_user = New ADODB.Connection
   Db_user.Open gstrCnn & file_user$
   Set Db_output = New ADODB.Connection
   Db_output.Open gstrCnn & file_output$

End Sub
```

Some aspects of ADO were professionally disappointing, such as the fact that the Find method in ADO can only search using SQL queries with a single search field. Thus, the following Find statement would result in a run time error:

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```
Tb_Usaeff.Find "TRTID = 'P0001' AND WEEDID = 'ECHCG'"
```

and the solution required an intricate (and most likely inefficient) configuration of single search field statements. Such an equivalent set of statements for the example above would be:

```
Tb_Usaeff.Find "TRTID = 'P0001'", 0, adSearchForward, adBookmarkCurrent
If Not Tb_Usaeff.EOF Then
        Do Until Tb_Usaeff.Fields("WEEDID") = 'ECHCG'
                Tb_Usaeff.Find "TRTID = 'P0001', 1, adSearchForward, adBookmarkCurrent
                If Tb_Usaeff.EOF Then Exit Do
        Loop
End If
```

An example in the code of such searches involving multiple criteria is as follows:

```
'Search for population change rates
Tb_poprate.Bookmark = CurrRecord
'JRW 06/12/03 - ADO Find can only handle a single field criteria, so
'           a search criteria having two criteria must be split manually
'Tb_poprate.Find "WEEDID >= '" & wdbio(ispec).id & "' AND CROPTILLID >= '" & curcrop.tilltype & "'"
Tb_poprate.MoveFirst
Tb_poprate.Find "WEEDID >= '" & wdbio(ispec).id & "'", 0, adSearchForward, adBookmarkCurrent
If Not Tb_poprate.EOF Then
   Do Until (Tb_poprate.Fields("CROPTILLID") >= CurCrop.tilltype)
      Tb_poprate.Find "WEEDID >= '" & wdbio(ispec).id & "'", 1, adSearchForward, adBookmarkCurrent
      If Tb_poprate.EOF Then Exit Do
   Loop
End If
```

However, some changes should most likely result in enhanced efficiency, such as the following procedures written for deleting all entries in a given database table:

```
Public Sub EmptyInputTableNamed(strTableName As String)
   'This procedure emptys the table in UserDB whose name is strTableName
   'P/F/GV Dependencies:   cnnUser
   'History:   JRW 10/18/03 - Initial Creation
   'Comments:  This procedure replaced the original EmptyTable procedure of Canner
   '           and associates as well as its intermediate predecessor EmptyWDEvents
   '           as it was found that in the long run it was more stable to use a
   '           single instance of an ADO command method rather than many instances
   '           of a ADO recordset delete method, especially when such tables became
   '           very large.
   Dim cmd As ADODB.Command
   Set cmd = New ADODB.Command
   cmd.ActiveConnection = cnnUser
   cmd.CommandType = adCmdText
   cmd.CommandText = "DELETE * FROM " & strTableName
```


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```
    cmd.Execute
    Set cmd = Nothing
End Sub

Public Sub EmptyOutputTableNamed(strTableName As String)
    'This procedure emptys the table in OutputDB whose name is strTableName
    'P/F/GV Dependencies:   cnnOutput
    'History:   JRW 10/18/03 - Initial Creation
    'Comments:  This procedure replaced the original EmptyTable procedure of Canner
    '           and associates as well as its intermediate predecessor EmptyWDEvents
    '           as it was found that in the long run it was more stable to use a
    '           single instance of an ADO command method rather than many instances
    '           of a ADO recordset delete method, especially when such tables became
    '           very large.
    Dim cmd As ADODB.Command
    Set cmd = New ADODB.Command
    cmd.ActiveConnection = cnnOutput
    cmd.CommandType = adCmdText
    cmd.CommandText = "DELETE * FROM " & strTableName
    cmd.Execute
    Set cmd = Nothing
End Sub

Public Sub EmptyParamTableNamed(strTableName As String)
    'This procedure emptys the table in ParamDB whose name is strTableName
    'P/F/GV Dependencies:   cnnParam
    'History:   JRW 10/20/03 - Initial Creation
    'Comments:  This procedure replaced the original EmptyTable procedure of Canner
    '           and associates as well as its intermediate predecessor EmptyWDEvents
    '           as it was found that in the long run it was more stable to use a
    '           single instance of an ADO command method rather than many instances
    '           of a ADO recordset delete method, especially when such tables became
    '           very large.
    Dim cmd As ADODB.Command
    Set cmd = New ADODB.Command
    cmd.ActiveConnection = cnnParam
    cmd.CommandType = adCmdText
    cmd.CommandText = "DELETE * FROM " & strTableName
    cmd.Execute
    Set cmd = Nothing
End Sub
```

Prior to their creation, such deletions were performed by deleting individual records one by one until BOF and EOF were both true.

In addition, methods like 'Edit', though used in DAO, were no longer necessary in ADO recordset objects. Also, in each instance where the 'NoMatch' property was used, the code was replaced with a check of whether or not EOF was true.

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